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The Impact of the Digital Economy on Carbon Emissions Based on Regional Development Imbalance

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Abstract: Digital economy is an important direction of the new round of technological revolution and a key driving force for realizing the "double control of carbon emissions". This paper utilizes the panel data of 30 provincial-level administrative regions in China from 2011 to 2021 to measure the development level of the digital economy, total carbon emissions, and carbon emission intensity and explores the impact of the digital economy on the dual control of carbon emissions and the mechanism of its effect by applying the mediating and moderating effect models. The results show that the digital economy can play a significant inhibitory effect on total carbon emissions and carbon emissions intensity, and this conclusion is still robust after a series of tests. From the government level, there exists a transmission path of "digital economy → environmental regulation stringency → dual control of carbon emissions"; from the enterprise and research organization level, there also exists a transmission path of "digital economy → R&D intensity → dual control of carbon emissions". From the perspective of regional imbalance, there are large regional differences in the impact of the digital economy on the dual control of carbon emissions, and there are also large differences in the impact of the various subdivided indicators of the digital economy on the dual control of carbon emissions. In addition, this paper also finds that the positive effect of the digital economy on the dual control of carbon emissions is more obvious in regions with a smaller proportion of SOEs. These findings add new evidence to the study of "the impact of the digital economy on the dual control of carbon emissions" and provide new ideas for accelerating the realization of green and sustainable development.

Keywords: digital economy; dual control of carbon emissions; environmental regulation stringency; regional development imbalance

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1. Introduction

The digital economy is considered the most significant economic form that has emerged after the agricultural and industrial economies. It has gradually become a new driving force for global economic development [1] and plays a crucial role in the new round of technological and industrial revolutions [2]. China is currently undergoing a critical transition to new from old economic engines [3]. As a national strategy, the development of the digital economy has risen to prominence, The Chinese Government explicitly states the need to accelerate the development of the digital economy and promote its deep integration with the real economy. A recently issued research report on China's digital economy development by the China Academy of Information and Communications Technology verified that China's digital economy reached CNY 50.2 trillion in 2022 [4], accounting for 41.5% of GDP. Figure 1. shows the growth rate of China's digital economy from 2016 to 2022 compared to the nominal growth rate of GDP, the data indicates that the growth rate of the digital economy is significantly higher than that of the GDP. This highlights the digital economy's role as an "accelerator" in China's economic development.

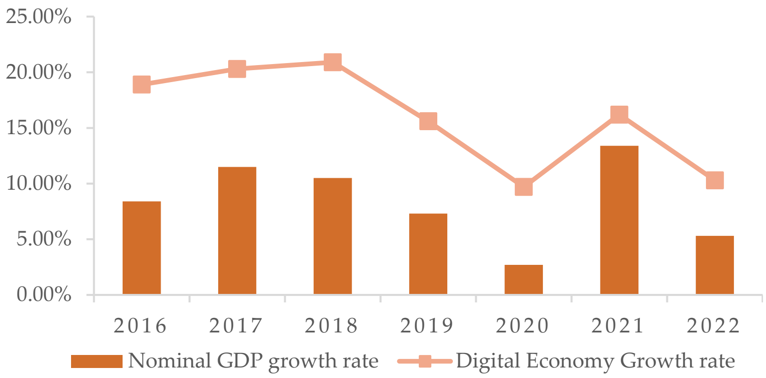

Figure 1. Digital economy growth rate vs. nominal GDP growth rate from 2016 to 2022.

Over the past 40 years of reform and opening up, China's economy has grown rapidly while its development thinking has matured [5]. The economic development model has gradually transformed and upgraded from the initial "crude growth model" to the "green and sustainable growth model" [6]. To achieve carbon peaking and carbon neutrality goals, China has implemented the "dual control of carbon emission" policy [7], which aims to control both the total amount of carbon emission and carbon emission intensity.

Against the backdrop of the global economic downturn and frequent extreme weather events, China, like other countries, faces the challenge of "balancing economic growth and environmental protection" [8]. With the rapidly developing digital economy, scholars are increasingly concerned about the impact of this sector on carbon emissions [9]. Several studies have demonstrated that at the enterprise level, the digital economy can enhance the sustainability of economic activities by boosting innovation and productivity throughout the industrial and supply chains [10]; at the market level, the digital economy can control carbon emissions by enhancing regional technological innovation capacity, improving resource mismatch, and facilitating industrial structure upgrading [11]. Some studies take the opposite view, although the digital economy can reduce energy consumption to a certain extent through communication technology, smart buildings, and telecommuting, the construction of its system is complex, generating large amounts of energy consumption during the infrastructure phase [12], and the long-term accumulation of carbon emission will hurt environmental quality [13].

Existing studies on the factors affecting carbon emission mainly focus on environmental regulation [14], international trade [15], and the digital transformation of enterprises [16]. Some studies also explore the relationship between the digital economy and carbon emissions. However, most of these studies only use total carbon emission or carbon emission intensity as an explained variable, ignoring the whole impact of the digital economy on both variables together.

Combined with the previous literature, this paper takes the data of 30 provincial-level administrative regions in China from 2011 to 2021 as the research sample and analyzes the relationship between the digital economy and dual control of carbon emissions from the following four aspects: First, to explore the impact of the digital economy on the total amount and intensity of carbon emissions in the context of the "dual control policy on carbon emissions" proposed by the Chinese government. Second, to investigate the positive effect of the mediating effect on the main regression by combining theoretical and empirical methods, taking the environmental regulation stringency at the government level and the research and development intensity at the enterprise and research organization level as the paths. Third, from the perspective of regional development heterogeneity, to explore the differences in the impact of the digital economy on dual control of carbon emissions in different regions, and to explore the differences in the impact of digital economy breakdown indicators on dual control of carbon emissions. Fourth, from the perspective of heterogeneity in the nature of property rights, to explore the moderating effect of the proportion of state-owned enterprise SOEs and non-SOEs on the relationship between the digital economy and the dual control of carbon emissions.

The main marginal contributions of this paper are as follows: (1) Focusing on China's dual-control policy on carbon emissions, this paper selects two explanatory variables, the absolute variable "total carbon emissions" and the relative variable "carbon emission intensity", to explore the relationship between the level of digital economy development and the level of carbon emissions in a more comprehensive way. (2) This paper is committed to exploring the intermediary path to realize the "dual control of carbon emission promoted by the digital economy. Starting from different perspectives, this paper constructs a government-level path based on "environmental regulation stringency" and an enterprise and research organization-level path based on "R&D intensity", which provides some empirical evidence for policy formulation and implementation. (3) This paper pays full attention to the impact of unbalanced and insufficient regional development in China on the dual control relationship between the digital economy and carbon emission. By combining theoretical and empirical methods, this issue is analyzed from the perspectives of property ownership characteristics, industrial structure, and economic foundations, which enriches the content of existing research.

2. Literature Review and Research Hypothesis

2.1. Digital Economy and Dual Control of Carbon Emission

The concept of a digital economy was first proposed by Tapscott in 1996 [17]. Since 1998, the U.S. Department of Commerce has published the report The Emerging Digital Economy for seven consecutive years. As a result, the digital economy has gained attention worldwide and has begun to develop rapidly. China's digital economy has undergone three stages of development: the budding period (1994–2002), the rapid development period (2003–2012), and the maturity period (2013–present). During the budding period of the digital economy, policies were centered around informatization and promoting the growth of e-commerce. This period witnessed an unparalleled expansion of portals, e-commerce platforms, and search engines, exemplified by companies such as Sina, Alibaba, and Baidu [18]. The rapid development period of the digital economy along with the number of Internet users ushered in sustained growth, this stage of socialization and shopping methods with the development of the digital economy has changed dramatically, as of the end of 2012, the size of China's Internet users has reached 564 million, the Internet penetration rate of 42.1%. Since 2013, China's digital economy has entered a mature period, accompanied by the rise of 4G networks and the advent of the mobile era of the internet [19].

In recent years, the proportion of carbon emissions from China's digital economy has significantly increased, from 0.80% in 2008 to 5.53% in 2018. It is projected that this proportion will continue to rise, reaching 11.63% by 2030. Although the proportion of carbon emissions from the digital economy has increased, it is important to objectively evaluate whether the industry itself is a high-energy consumer. This paper discusses the impact of the digital economy on carbon emissions from both the supply-side and demand-side perspectives.

Supply-side perspectives. For the manufacturing industry, the high energy demand inevitably makes them the "hardest hit" by carbon emissions [20]. In the new round of the industrial revolution, the industrial internet has become an inevitable trend to promote the manufacturing industry from the traditional mode to the digital mode. Specifically, the digital economy can help manufacturing firms realize real-time monitoring and control of the energy production process which improves the efficiency of processing and conversion, as well as the efficiency of energy transmission, distribution, and storage [21]. In essence, it can optimize the energy structure to significantly reduce unnecessary carbon emissions and achieve sustainable low-carbon production methods [22].

For the service industry, as an important engine of economic development, such firms should have a keen sense of smell in the era of the digital economy [23]. The modern service industry is deeply integrated with the digital economy through technology R&D,

software design, and platform operation to generate a stronger resource clustering effect, thus optimizing energy allocation efficiency and reducing transaction costs [24]. A mature digital economy industry chain can be widely used in many fields such as production, distribution, and circulation, accelerating the low-carbon transformation of the whole industry and ultimately realizing a positive effect on carbon emission control [25]. In the long run, the internet platform built based on digital technology in the service industry can also be used to accelerate social development and improve people's livelihood by injecting new impetus into the process of green and sustainable development.

Demand-side perspectives. The digital economy has injected new vitality into the existing energy demand system. The development of the digital economy can improve the accuracy and timeliness of carbon emission information which helps the government to realize macro-control and enterprises to realize efficient carbon emission management [26]. Specifically, digital technology can help local governments to gather new types of production factors such as technology, management, and data, and engage in deep cooperation with regions with cleaner energy structures through complementary resources and technology exchange [27]. For example, thanks to the characteristics of the digital economy, which is not heavily dependent on land and labor, the "counting from the East to the West " project not only proposes a new solution to the problem of unbalanced regional development but also becomes a key initiative to achieve double control of carbon emissions [28].

In addition, digital technology has made it possible to target carbon emission sources, detect carbon emissions, and measure other environmental indicators. In China, for example, in the context of the booming digital economy and the continuous improvement of market regulations, China has established a number of digital technology-based trading platforms for carbon emission rights [29], energy consumption rights, and wastewater rights, which have prompted high-carbon firms to phase out energy-consuming production capacity to reduce the total amount and intensity of carbon emissions. Based on the above analysis, this paper proposes Hypotheses 1a and 1b:

H1a. *The digital economy has a positive impact on controlling total carbon emissions.*

H1b. *The digital economy has a positive impact on controlling carbon emission intensity.*

2.2. Digital Economy, Environmental Regulation, and Dual Control of Carbon

Digital technology, as an important carrier of a new generation of information and communication technologies such as 5G, artificial intelligence, and cloud computing, has supported the development of emerging industries and the transformation of digital governance in society [30] and promoted energy conservation and emission reduction in energy-consuming industries, it cannot be ignored that with the explosive growth of data volume, it has led to a significant increase in energy consumption for data transmission, storage, computation, application links, and interconnected devices [31]. Because of the lag of market regulation, for the digital economy in the period of rapid development, if we need to maintain the sustainable positive impact of the digital economy on the dual control of carbon emissions cannot only rely on the spontaneous regulation of the market, but also should take into full consideration of the government's macro-control.

According to the "reverse emission reduction effect", the government's continuous improvement of environmental regulation standards can force high-energy-consuming firms to seek technological innovation and improve pollution treatment capacity, and ultimately achieve the purpose of emission reduction [32]. Since the development of the market economy, China's environmental regulation policy category has gradually changed from "government intervention" to "market incentives" and "public participation" [33]. Existing studies have also demonstrated that the implementation of energy quota trading policies formulated based on utilizing market mechanisms is more effective than command-and-control policies based on mandatory regulatory restrictions [34]. The reason for this is that environmental regulations formulated based on market mechanisms are more flexible and incentive-based, which can better utilize the potential of the market in resource allocation, and incentivize enterprises to improve the efficiency of energy use, to reduce the scale of energy consumption, and ultimately achieve low-carbon development [7]. Based on the above analysis, this paper proposes Hypothesis 2:

H2. *The development of the digital economy has a positive impact on the dual control of carbon emissions by increasing environmental regulation stringency.*

2.3. Digital Economy, R&D Intensity, and Dual Control of Carbon

The digital economy relies on the support of R&D activities in promoting the process of dual control of carbon emissions. First, R&D can effectively optimize industrial structure [35]. An important tendency of the development of the digital economy is to promote the low-carbon development of high-tech industries and reduce the reliance on high-carbon emission industries, a process that relies on sustained R&D investment to realize. Second, R&D helps to improve the level of technological innovation [36]. Innovation in the digital economy is a key factor in promoting the development of the digital economy, and the breakthroughs and application of artificial intelligence, big data, cloud computing, and other technologies can effectively improve the efficiency of energy use and optimize the production process, reduce the waste of resources and ultimately achieve the dual control of carbon emissions [37]. Third, to meet the market demand and expectations of external stakeholders [38]. As the climate environment becomes increasingly severe, countries around the world are paying more attention to carbon emission reduction. To meet the market, investor, and consumer demand for low-carbon technologies, companies will increase the intensity of R&D and actively respond to the call for carbon reduction to meet the needs of all parties [39]. Based on the above analysis, this paper proposes Hypothesis 3:

H3. *The development of the digital economy has a positive impact on the dual control of carbon emissions by increasing R&D intensity.*

2.4. Hypotheses Related to Heterogeneity

2.4.1. Regional Imbalances in the Impact of Digital Economy on Carbon Emissions

On the whole, the digital economy has played a positive role in the dual control of carbon emissions, but it is undeniable that the problem of imbalanced regional economic development due to location conditions, resource endowment, economic foundation, and other reasons will make the implementation effect show significant geographical differences.

The proportion of traditional industries in the central region is relatively high, and through the promotion of the digital economy, industrial upgrading and transformation can be realized more effectively and carbon emission intensity can be reduced. In recent years the Central China research and innovation platform centered on Hefei, Wuhan, Changsha, and Zhengzhou has gradually formed, with strong policy support and a large population base, providing a solid foundation for the green transformation of its digital economy [40]. This in the central region may, to some extent, enable it to outperform the eastern region, which is dominated by service and high-tech industries, in terms of carbon reduction [41].

The western and northeastern regions have unique advantages in terms of natural resources and potential markets. In the case of the West, it is rich in wind and solar energy, and in recent years has been supported by the Belt and Road Initiative [42]. The northeast region has a relatively well-developed industrial system, which can provide a foundation for the digital low-carbon transformation of traditional industries [43]. However, the western and northeastern regions may be relatively weak in terms of their digital economy industrial base and innovation capacity, which to some extent limits their potential for carbon reduction.

The eastern region, as a pioneer of the digital economy and low-carbon industries, also has certain problems in promoting the digital economy to help dual control of carbon emissions. On the one hand, the market in the eastern region is not only highly competitive but also nearly saturated, and market saturation may limit the release of its carbon reduction potential [44]. On the other hand, the eastern region is highly sensitive to costs, and as the highland of China's economy, its labor and innovation costs are significantly higher than those of other regions [45]. As a result, the marginal effect of digital economy-driven dual control of carbon emissions will be relatively low. Based on the above analysis, this paper proposes research Hypothesis 4a:

H4a. *There are regional imbalances in the positive impact of the digital economy on carbon emissions.*

2.4.2. Differences in the Impact of Digital Economy Segmented Metrics on Carbon Emissions

The differences in the impact of the development of the digital economy on carbon emissions can also be reflected in the digital economy segmented metrics. First, the digital users. The scale of digital users, as measured by mobile phone subscribers, telecommunications and postal services, and express delivery volume, has a strong universality, and with the rapid expansion of the scale of users in the digital economy, it will inevitably reduce the marginal cost of carbon emissions from the development of the digital economy [46]. For example, the continuous optimization of online work lifestyles such as e-mail, video conferencing, and online shopping will reduce carbon emissions that may be generated by offline activities such as commuting and shopping [47]. Second, the digital infrastructures. Although the digital economy in the central and western regions is booming, it is undeniable that its "resource-based" characteristics have for a long time led to some extent to the problems of imperfect infrastructure, especially in some areas with remote locations and poor natural environments, which makes it difficult to carry out the construction of digital infrastructure [48]. The uneven development of digital infrastructure is one of the important reasons for the uneven development of the region, and there is a certain degree of uncertainty in the use of digital infrastructure to promote the regional synergistic dual control of carbon emissions. Third, the digital industry. A number of projects represented by "Counting from the East to the West" have made great contributions to promoting cross-regional and cross-sectoral synergetic development, and added bricks and mortar to the development pattern of clean energy in the western region [49]. China's digital industry clusters have formed a favorable situation of "leading in the eastern region and rising in the central and western regions", which gradually makes up for the lack of digital economy in the central and western regions, thus improving the dual control ability of carbon emissions [50]. Fourth, the digital innovation. The development of the digital economy in the eastern region is earlier, the system is more solid compared to the central and western regions, and the attraction of funds and talents is greater, which has led to the problem of a shortage of digital technology funds and talents in the central and western regions, and the difference in regional development has led to more resistance in the central and western regions to use the digital innovation environment to pull the dual control process of carbon emissions [51]. Based on the above analysis, this paper proposes research Hypothesis 4b:

H4b. *Different digital economy segmented indicators have different impacts on carbon emissions.*

2.4.3. Heterogeneity Analysis Based on Property Ownership Characteristics

From the perspective of stakeholder theory, more and more investors and shareholders pay more attention to the sustainable development and social responsibility of enterprises [52], and since the financing constraints of non-SOEs are stronger than those of SOEs [53], coupled with the influence of information asymmetry, non-SOEs need to pay more practical actions to gain the trust of external stakeholders, including potential investors [54]. Therefore, in order to reduce carbon emissions, non-SOEs will put more human and financial resources into green innovation, and the digital economy also provides a better platform for green innovation of enterprises.

From the perspective of rent-seeking theory, the root cause of rent-seeking is the government's intervention in the market [55], and since SOEs have stronger political connections with the government than non-SOEs, their rent-seeking costs will be lower [56]. Although low-cost rent-seeking brings sufficient resources and profits to SOEs, it also makes SOEs more inclined to obtain privileges through rent-seeking, which may induce mismatch and waste of resources as well as malfunction of market regulation [57]. Instead of improving market competitiveness by increasing innovation and productivity. Such behavior is not only detrimental to the green innovation and sustainable development of SOEs but also affects the development of the regional digital economy and the process of dual control of carbon emissions. Based on the above analysis, this paper proposes research Hypothesis 4c:

H4c. *The impact of the digital economy on carbon dual control is more positive in regions with a high proportion of non-SOE.*

The framework of this paper is shown in Figure 2:

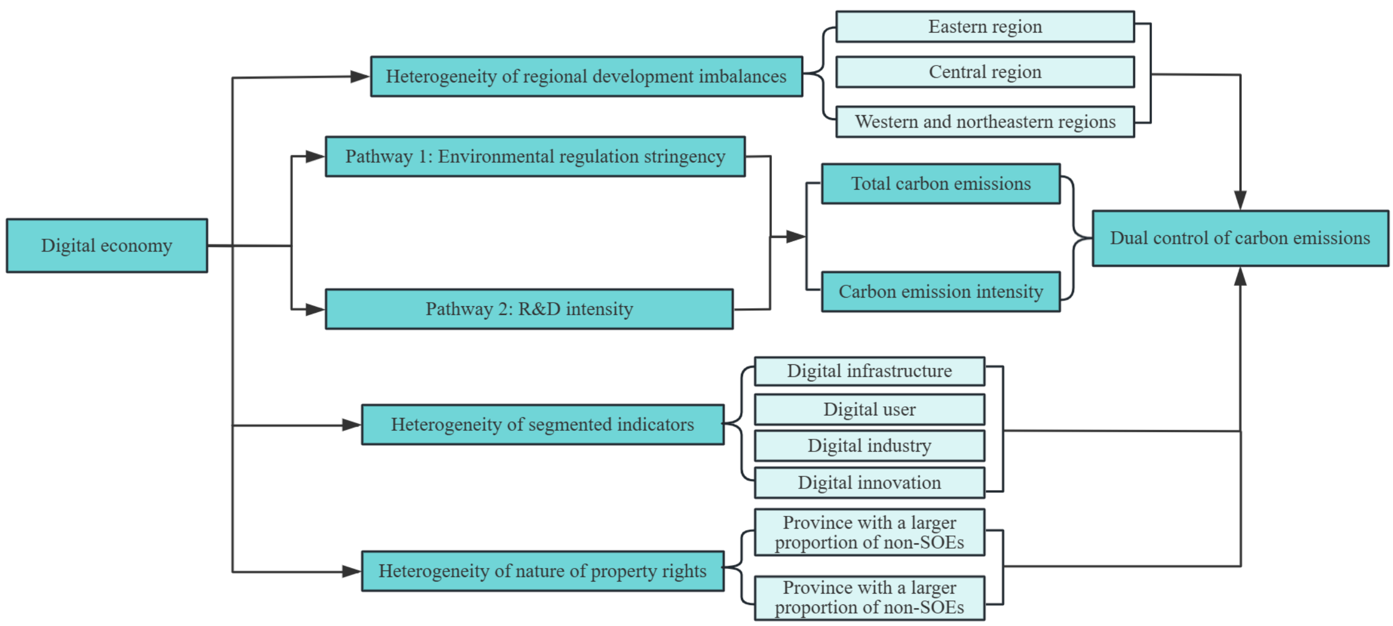

Figure 2. Framework for this paper.

3. Methodology and Data

3.1. Variables Selection and Measurement

3.1.1. Explained Variables

This study focuses on two explained variables: total carbon emissions (*CE*) and carbon emission intensity (*CI*). To calculate these explained variables, this paper follows the methodology of Chang et al. [58], using the following specific model:

$$EC = \sum_{i=1}^{7} EC_i = \sum_{i=1}^{7} E_i \times CF_i \times CC_i \times COF_i \times 3.67 \quad (1)$$

$$CP = Q \times EF_{cement} \quad (2)$$

$$CE = EC + CP \quad (3)$$

$$CI = \frac{CE}{GDP} \quad (4)$$

Model (1)–(3) represents total carbon emissions related to the combustion of seven major fossil energy sources and from the production of cement. *CE* represents CO_2 emissions. *EC* represents CO_2 emissions from the combustion of seven major fossil energy sources. *CP* represents CO_2 emissions from the production of cement. *i* represents the type of energy, including coal, coke, gasoline, kerosene, diesel, fuel oil, and natural gas. E_i represents the consumption of energy *i*. CF_i represents the calorific value of energy *i*. CC_i represents the carbon content of energy *i*. COF_i represents an oxidizing factor of energy *i*. $CF_i \times CC_i \times COF_i \times 3.67$ represents the CO_2 emission factor of energy *i*. *Q* represents the quantity of cement production. EF_{cement} represents the CO_2 emission factor of cement production. Model (4) represents carbon emission intensity, which is calculated using the region's total carbon emissions to GDP ratio.

3.1.2. Core Explanatory Variable

The core explanatory variable of this study is the digital economy (*DIGE*). This paper categorizes the digital economy into four segmented indicators: digital infrastructure, digital user, digital industry, and digital innovation, and the four primary indicators are further divided into sixteen secondary indicators. The entropy method is used to assign weights to the sixteen secondary indicators [51]. Referring to the metrics of Li et al. [59], He et al. [60], Lu et al. [61], and Zhao et al. [62], this paper uses the entropy method to measure the level of development of the digital economy, and the results are presented in Table 1.

Table 1. Digital economy indicators evaluation indicator system.

Explanatory Variable	Primary Indicator	Secondary Indicators	Unit	Indicator Attribute	Weights
Digital Economy	Digital infrastructure	Number of cell phone base stations	10^4 pcs	Positive	0.038
		Number of Internet access ports	10^4 pcs	Positive	0.037
		Number of websites	10^4 pcs	Positive	0.070
		Length of fiber optic line	kilometers	Positive	0.037
	Digital user	Number of cell phone subscribers	10^4 households	Positive	0.032
		Volume of telecommunication services	CNY 10^8	Positive	0.065
		Volume of postal operations	CNY 10^8	Positive	0.106
		Volume of express mail	10^4 pcs	Positive	0.114
	Digital industry	Investment in fixed assets in the information transmission, computer services, and software industry	CNY 10^8	Positive	0.036
		Revenue from electronic information manufacturing	CNY 10^8	Positive	0.099
		Revenue from software operations	CNY 10^8	Positive	0.093
		Number of employees in the information transmission, software, and information technology services industry	10^4 pcs	Positive	0.059
	Digital Innovation	R&D expenses	CNY 10^8	Positive	0.059
		Number of patents granted for inventions	pcs	Positive	0.088
		Gross domestic production	CNY 10^8	Positive	0.037
		Funding for education	CNY 10^8	Positive	0.030

3.1.3. Mediating Variable

Environmental regulation stringency (ER). Referring to the metric of Song et al. [63], environmental regulation stringency is calculated using the ratio of a completed investment in industrial pollution to the value added by the industry.

R&D intensity (RDI). Referring to the metric of Qin et al. [64], R&D intensity is calculated using the ratio of R&D expenditures to GDP in each province.

3.1.4. Moderating Variable

Property ownership characteristics (PC). Referring to the metric of Sun [65], property ownership characteristics are expressed as the ratio of SOEs to all enterprises in each province.

3.1.5. Control Variables

To better identify the impact of digital economy development on the progress of dual control of carbon emissions, referring to the metric of Li et al. [66], Huang et al. [67], Wang et al. [68], and Kuziboev et al. [69], this paper sets a series of control variables that may have an impact on the dual control of carbon emissions concerning the existing literature: industrial structure (*IS*, shown as the ratio of tertiary sector output to secondary sector output), level of urbanization (*UL*, shown as the ratio of urban population to total population), foreign direct investment (*FDI*, shown as the ratio of total FDI*USD-RMB exchange rate to regional GDP), level of external openness (*LEOP*, shown as ratio of total import and export of goods*USD-RMB exchange rate to regional GDP), tax burden level (*TB*, shown as ratio of tax revenue to regional GDP).

3.2. Data Sources

This study examines a panel dataset of 330 provincial-level administrative regions in China from 2011 to 2021. The data about the digital economy were sourced from *the China Statistical Yearbook*, *the China Information Industry Yearbook*, and *the official website of the Ministry of Industry and Information Technology of the People's Republic of China*. Meanwhile, the data related to carbon dioxide were obtained from *Carbon Emission Accounts and Datasets*, *the China Economic Database*, and *the China Energy Statistical Yearbook*. The table below presents the descriptive statistics for each variable. Table 2 provides a statistical description of the aforementioned variables.

Table 2. Statistical description of variables.

Variable	Sample Size	Average	Standard Deviation	Minimum	Median	Maximum
CE	330	10.31	0.751	8.353	10.350	12.220
CI	330	2.004	1.604	0.196	1.539	10.560
DIGE	330	0.111	0.113	0.002	0.072	0.595
ER	330	0.003	0.004	0.000	0.002	0.031
RDI	330	0.017	0.011	0.004	0.014	0.065
PC	330	0.460	0.133	0.130	0.459	0.699
IS	330	1.246	0.705	0.518	1.083	5.297
UL	330	0.596	0.121	0.350	0.581	0.896
FDI	330	0.019	0.015	0.000	0.017	0.080
LEOP	330	0.265	0.291	0.008	0.142	1.548
TB	330	0.082	0.029	0.044	0.075	0.200

3.3. Empirical Model Construction

3.3.1. Baseline Econometric Model

To examine the effect of the digital economy on the dual control of carbon emission, this study establishes the following baseline econometric model:

$$CE_{it} = \alpha_0 + \alpha_1 DIGE_{it} + \alpha_2 \Sigma Control_{it} + \mu_t + \lambda_i + \varepsilon_{it} \quad (5)$$

$$CI_{it} = \alpha_0 + \alpha_1 DIGE_{it} + \alpha_2 \Sigma Control_{it} + \mu_t + \lambda_i + \varepsilon_{it} \quad (6)$$

where CE_{it} represents the total carbon emissions of province i in year t, CI_{it} represents the carbon emission intensity of province i in year t, $DIGE_{it}$ represents the digital economy of province i in year t, $\Sigma Control_{it}$ represents the sum of a series of control variables of province i in year t, μ_t represents the fixed effects of the province, λ_i represents the fixed effects of time.

3.3.2. Mediating Effects Model

To examine the mediating effect of "digital economy $\rightarrow$ environmental regulation stringency $\rightarrow$ dual control of carbon emission", this study establishes the following recursive equation model:

$$C_{it} = \beta_0 + \beta_1 Dige_{it} + \beta_2 \Sigma Control_{it} + \mu_t + \lambda_i + \varepsilon_{it} \tag{7}$$

$$ER_{it} = \beta_0 + \beta_1 Dige_{it} + \beta_2 \Sigma Control_{it} + \mu_t + \lambda_i + \varepsilon_{it} \tag{8}$$

$$C_{it} = \beta_0 + \beta_1 Dige_{it} + \beta_2 ER_{it} + \beta_3 \Sigma Control_{it} + \mu_t + \lambda_i + \varepsilon_{it} \tag{9}$$

where C_{it} represents the dual control of carbon emission of province i in year t (CE_{it} and CI_{it}), ER_{it} represents environmental regulation stringency of province i in year t, the meanings of the remaining variables are consistent with Models (5) and (6).

To examine the mediating effect of "digital economy $\rightarrow$R&D intensity$\rightarrow$ dual control of carbon emission", this study establishes the following recursive equation model:

$$C_{it} = \gamma_0 + \gamma_1 Dige_{it} + \gamma_2 \Sigma Control_{it} + \mu_t + \lambda_i + \varepsilon_{it} \tag{10}$$

$$RDI_{it} = \gamma_0 + \gamma_1 Dige_{it} + \gamma_2 \Sigma Control_{it} + \mu_t + \lambda_i + \varepsilon_{it} \tag{11}$$

$$C_{it} = \gamma_0 + \gamma_1 Dige_{it} + \gamma_2 RDI_{it} + \gamma_3 \Sigma Control_{it} + \mu_t + \lambda_i + \varepsilon_{it} \tag{12}$$

where C_{it} represents the dual control of carbon emission of province i in year t (CE_{it} and CI_{it}), RDI_{it} represents R&D intensity of province i in year t, the meanings of the remaining variables are consistent with Models (5) and (6).

3.3.3. Moderating Effects Model

To examine the moderating effect of property ownership characteristics on the relationship between the digital economy and dual control of carbon emission, this study establishes the following model:

$$C_{it} = \delta_0 + \delta_1 DIGE_{it} + \delta_2 PC_{it} + \delta_3 DIGE_{it} \times PC_{it} + \delta_4 \Sigma Control_{it} + \mu_t + \lambda_i + \varepsilon_{it} \tag{13}$$

where C_{it} represents the dual control of carbon emission of province i in year t (CE_{it} and CI_{it}), PC_{it} represents property ownership characteristics of province i in year t, $DIGE_{it} \times PC_{it}$ represents the interaction term between digital economy and dual control of carbon emission, the meanings of the remaining variables are consistent with Models (5) and (6).

4. Empirical Results

4.1. Baseline Regression Result

4.1.1. Digital Economy and Total Carbon Emissions

Columns (1) and (2) of Table 3 report the results of the baseline regression on the impact of the digital economy on total carbon emissions. The results without control variables are shown in column (1) and the results after adding control variables are shown in column (2). The results show that the coefficient of the core explanatory variable digital economy is significantly negative at the 1% level, regardless of whether control variables are added or not. The regression results support Hypothesis 1a.

Table 3. Results of baseline regression.

Variables	(1) CE	(2) CE	(3) CI	(4) CI
DIGE	−0.884 ***	−1.200 ***	−1.561 **	−2.978 ***
	(−4.441)	(−5.946)	(−2.627)	(−3.817)
IS		−0.260 ***		−0.563 **
		(−5.877)		(−3.290)
UL		1.256 *		−9.045 ***
		(2.025)		(−3.774)
FDI		0.763		−0.439
		(0.894)		(−0.133)
LEOP		−0.354 **		−0.372
		(−3.050)		(−0.831)
TB		2.103 **		15.976 ***
		(2.723)		(5.352)
Province fixed effects	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES
Constant	10.286 ***	9.791 ***	2.589 ***	6.814 ***
	(444.774)	(28.368)	(28.941)	(5.108)
Observations	330	330	330	330
R-squared	0.077	0.252	0.171	0.329

Note: *, **, and *** are statistically significant at 10%, 5%, and 1%, respectively. The content in parentheses is *t*-value.

4.1.2. Digital Economy and Carbon Emission Intensity

Columns (3) and (4) of Table 3 report the results of the baseline regression on the impact of the digital economy on carbon emission intensity. The results without control variables are shown in column (1) and the results after adding control variables are shown in column (2). The results show that the coefficient of digital economy is significantly negative at the 5% level without adding control variables, and the coefficient of digital economy is significantly negative at the 1% level after adding control variables. The regression results support Hypothesis 1b.

4.2. Mediating Effects of Environmental Regulation Stringency

It has been verified that the digital economy can have a direct and significant positive impact on the dual control of carbon emissions. Through the theoretical analysis, it can be seen that the digital economy may also have an indirect effect on the dual control of carbon emissions through environmental regulation, to verify the hypothesis, this part of the recursive equation to test the mediating effect of “digital economy-environmental regulation-dual control of carbon emissions”.

The results of the regressions for Models (7)–(9) are presented in Table 4. As shown in columns (1) and (4), the coefficient of the digital economy is significantly negative at the 1% level when total carbon emissions and carbon emission intensity are the explained variables, indicating that the digital economy has a positive impact on the dual control of carbon emissions. As shown in column (2), when environmental regulation stringency is the explained variable, the coefficient of the digital economy is significantly positive at the 1% level, indicating that the development of the digital economy can have a positive impact on environmental regulation stringency. At the same time, as shown in columns (3) and (5), when environmental regulation stringency is the core explanatory variable, the coefficients of total carbon emissions and carbon emission intensity are significantly negative at the 1% and 5% levels, indicating that the more stringent the environmental regulation, the more effective the dual control of carbon emissions. The regression results support Hypothesis 2.

Table 4. Results of environmental regulation stringency as a mediating variable.

Variables	(1) CE	(2) ER	(3) CE	(4) CI	(5) CI
DIGE	−1.200 ***	0.018 ***	−1.098 ***	−2.978 ***	−2.445 **
	(−5.946)	(3.930)	(−5.330)	(−3.817)	(−3.094)
ER			−5.811 *		−30.147 **
			(−2.198)		(−2.971)
IS	−0.260 ***	0.000	−0.260 ***	−0.563 **	−0.562 ***
	(−5.877)	(0.034)	(−5.913)	(−3.290)	(−3.329)
UL	1.256 *	−0.030 *	1.081	−9.045 ***	−9.954 ***
	(2.025)	(−2.181)	(1.740)	(−3.774)	(−4.175)
FDI	0.763	0.019	0.876	−0.439	0.146
	(0.894)	(1.019)	(1.031)	(−0.133)	(0.045)
LEOP	−0.354 **	0.005	−0.326 **	−0.372	−0.232
	(−3.050)	(1.803)	(−2.819)	(−0.831)	(−0.521)
TB	2.103 **	−0.019	1.995 **	15.976 ***	15.414 ***
	(2.723)	(−1.082)	(2.595)	(5.352)	(5.224)
Province fixed effects	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES
Constant	9.791 ***	0.018 *	9.894 ***	6.814 ***	7.349 ***
	(28.368)	(2.303)	(28.593)	(5.108)	(5.533)
Observations	330	330	330	330	330
R-squared	0.252	0.266	0.262	0.329	0.347

Note: *, **, and *** are statistically significant at 10%, 5%, and 1%, respectively. The content in parentheses is *t*-value.

4.3. Mediating Effects of R&D Intensity

Through the theoretical analysis, it can be seen that the digital economy may also have an indirect effect on the dual control of carbon emissions through R&D intensity, to verify the hypothesis, this part of the recursive equation to test the mediating effect of "digital economy-R&D intensity-dual control of carbon emissions".

The results of the regressions for Models (10)–(12) are presented in Table 5. As shown in columns (1) and (4), the coefficient of the digital economy is significantly negative at the 1% level when total carbon emissions and carbon emission intensity are the explained variables, indicating that the digital economy has a positive impact on the dual control of carbon emissions. As shown in column (2), when R&D intensity is the explained variable, the coefficient of the digital economy is significantly positive at the 1% level, indicating that the development of the digital economy can have a positive impact on R&D intensity. At the same time, as shown in columns (3) and (5), when R&D intensity is the core explanatory variable, the coefficients of total carbon emissions and carbon emission intensity are significantly negative at the 5% and 10% levels, indicating that the greater the R&D intensity, the more effective the dual control of carbon emissions. The regression results support Hypothesis 3.

Table 5. Results of R&D intensity as a mediating variable.

Variables	(1) CE	(2) RDI	(3) CE	(4) CI	(5) CI
DIGE	−1.200 ***	0.015 ***	−0.568 **	−2.978 ***	−1.799 *
	(−5.946)	(6.468)	(−3.216)	(−3.817)	(−2.588)
RDI			−20.569 ***		−37.517 *
			(−4.775)		(−2.214)
IS	−0.260 ***	−0.001	−0.590 ***	−0.563 **	−0.590 ***
	(−5.877)	(−1.317)	(−3.440)	(−3.290)	(−3.440)
UL	1.256 *	−0.007	−8.940 ***	−9.045 ***	−8.940 ***
	(2.025)	(−0.866)	(−3.749)	(−3.774)	(−3.749)

Table 5. *Cont.*

Variables	(1) CE	(2) RDI	(3) CE	(4) CI	(5) CI
FDI	0.763	0.001	−0.992	−0.439	−0.992
	(0.894)	(0.078)	(−0.302)	(−0.133)	(−0.302)
LEOP	−0.354 **	0.001	−0.418	−0.372	−0.418
	(−3.050)	(0.459)	(−0.916)	(−0.831)	(−0.916)
TB	2.103 **	0.012	16.836 ***	15.976 ***	16.836 ***
	(2.723)	(1.155)	(5.635)	(5.352)	(5.635)
Province fixed effects	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES
Constant	9.791 ***	0.061 ***	9.894 ***	6.814 ***	7.349 ***
	(28.368)	(7.866)	(28.593)	(5.108)	(5.533)
Observations	330	330	330	330	330
R-squared	0.252	0.886	0.883	0.329	0.841

Note: *, **, and *** are statistically significant at 10%, 5%, and 1%, respectively. The content in parentheses is *t*-value.

4.4. Robustness Test and Endogeneity Treatment

4.4.1. Replacing Explained Variables

The explained variables "total carbon emissions" and "carbon emission intensity" in the baseline regression are replaced by "carbon productivity" (CP) in the robustness test, as an alternative way to measure the impact of the digital economy on the dual control of carbon emissions. Since "carbon productivity" is a positive indicator, the expected relationship between the digital economy and carbon emission efficiency is that the higher the level of development of the digital economy, the higher the carbon productivity, i.e., the two have a positive relationship. Column (1) of Table 6 reports the regression results, which show that the regression coefficient for the digital economy is significantly positive at the 1% level and the baseline regression still holds.

$$CP = \frac{GDP}{CE} \tag{14}$$

Table 6. Results of robustness test.

	Replacing Explained Variables	Excluding Municipality Samples		Adding Control Variables	
	CI	CE	CI	CE	CI
	(1)	(2)	(3)	(4)	(5)
DIGE	2.733 ***	−1.138 ***	−3.747 ***	−1.332 ***	−2.812 ***
	(10.699)	(−6.028)	(−5.344)	(−6.498)	(−3.529)
IS	0.181 **	−0.329 ***	−0.886 ***	−0.238 ***	−0.641 ***
	(3.239)	(−6.211)	(−4.505)	(−5.274)	(−3.657)
UR	−4.173 ***	1.010	−13.121 ***	0.914	−8.473 ***
	(−5.317)	(1.189)	(−4.158)	(1.461)	(−3.482)
FDI	3.984 ***	0.786	−3.601	0.247	−1.436
	(3.687)	(0.687)	(−0.847)	(0.282)	(−0.422)
LEOP	−0.638 ***	−0.416 *	−0.169	−0.236	−0.349
	(−4.352)	(−2.526)	(−0.276)	(−1.931)	(−0.736)
TB	−11.893 ***	1.123	19.435 ***	3.119 **	10.760 **
	(−12.166)	(1.093)	(5.094)	(3.124)	(2.772)
GI				3.119 **	10.760 **
				(3.124)	(2.772)
ED				0.233	3.622 *
				(0.528)	(2.112)

Table 6. *Cont.*

	Replacing Explained Variables	Excluding Municipality Samples		Adding Control Variables	
	CI	CE	CI	CE	CI
	(1)	(2)	(3)	(4)	(5)
Province fixed effects	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES
Constant	3.523 ***	10.162 ***	8.814 ***	6.632 ***	3.442
	(8.065)	(22.757)	(5.313)	(5.169)	(0.690)
Observations	330	286	286	330	330
R-squared	0.809	0.270	0.394	0.268	0.337

Note: *, **, and *** are statistically significant at 10%, 5%, and 1%, respectively. The content in parentheses is *t*-value.

4.4.2. Excluding Municipality Samples

The digital economy of municipalities develops faster and has a more obvious locational advantage than other provinces, which may have some impact on the main regression results, so this part excludes the data of Beijing, Tianjin, Shanghai, and Chongqing from the robustness test, and recalculates the level of digital economy development in each province by the entropy method and runs the regression. Columns (2) and (3) of Table 6 report the regression results, which show that the regression coefficient of the digital economy is significantly negative at the 1% level and the baseline regression still holds.

4.4.3. Adding Control Variables

The degree of government intervention (GI) and the level of economic development (ED) to a large extent can also affect the relationship between the digital economy and the dual control of carbon emissions, government intervention is the government's macro-control under the conditions of market economy, to make up for the disadvantages of market regulation spontaneity, blindness, lagging and so on, and the level of economic development embodies the degree of wealth of a region, so in the robustness test to add these two control variables to re-test regression. GI is measured by the ratio of fiscal expenditure to gross regional product, and ED is measured by price-deflating GDP per capita. Columns (4) and (5) of Table 6 report the regression results, which show that the regression coefficients for the digital economy are significantly negative at the 1% level, and the baseline regression still holds.

4.4.4. Endogeneity Treatment

The results of the baseline regression show that the digital economy will have a positive impact on the dual control of carbon emissions, i.e., the digital economy is negatively correlated with total carbon emissions and carbon emission intensity. However, it is worth noting that there may still be endogeneity problems in the baseline regression model due to omitted variables and bidirectional causality. Therefore, this paper takes the digital economy development level of each province lagged by one period (DIGE_1) as an instrumental variable for the endogeneity test. Columns (1) and (2) of Table 7 report the endogeneity test results of the relationship between digital economy and total carbon emissions, which show that the coefficient of total carbon emissions is still significantly negative at the 1% level. Columns (3) and (4) of Table 7 report the endogeneity test results of the relationship between the digital economy and carbon emission intensity, which show that the relationship between the digital economy and carbon intensity is negative at the 1% level. In addition, the Kleibergen–Paap rk LM statistic results for both sets of endogeneity tests reject the initial hypothesis of under-identification of instrumental variables at the 1% level. In summary, the baseline regression results still hold when endogeneity is taken into account.

Table 7. Results of endogeneity test.

	DIGE(CE) (1)	CE (2)	DIGE(CI) (3)	CI (4)
DIGE		−1.111 ***		−2.911 ***
Control variables	YES	YES	YES	YES
DIGE_1	1.017 ***		1.015 ***	
Province fixed effects	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES
Kleibergen–Paap rk LM statistic	31.36 ***		31.87 ***	
Kleibergen–Paap Wald rk F statistic	305.92		316.83	

Note: *, **, and *** are statistically significant at 10%, 5%, and 1%, respectively.

5. Further Analysis

5.1. Heterogeneity Analysis Based on Different Economic Regions

Table 8 shows the regression results of the heterogeneity analysis of the impact of the digital economy on the dual control of carbon emissions in different economic regions. The regression results show that there is obvious geographical heterogeneity in the impact of digital economy on dual control of carbon emissions: in the eastern region, as shown in columns (1) and (4), the coefficients of the digital economy are insignificant at the 10% level and significantly positive at the 10% level, respectively; in the central region, as shown in columns (2) and (5), the coefficients of the digital economy are significantly negative at the 1% level; and in the northeastern and southwestern regions, as shown in columns (3) and (6), the coefficients of the digital economy are significantly positive at the 5% and 10% levels, respectively. This result clearly indicates that the positive impact of the digital economy on dual control of carbon emissions is ranked as follows: central region > western region and northeast region > eastern region. Hypothesis 4a is confirmed.

Table 8. Results of heterogeneity analysis based on different economic regions.

	CE			CI		
	Eastern Region (1)	Central Region (2)	Western and Northeastern Region (3)	Eastern Region (4)	Central Region (5)	Western and Northeastern Region (6)
DIGE	0.052	−7.361 ***	−1.726 **	0.712 *	−26.380 ***	−1.748 *
	(0.321)	(−6.427)	(−2.824)	(2.544)	(−4.319)	(−1.972)
IS	−0.030	−0.742 ***	−0.218 **	0.005	−2.958 **	−0.184
	(−0.827)	(−3.926)	(−2.994)	(0.075)	(−2.936)	(−0.859)
UR	1.937 ***	6.773 *	1.754	−3.656 ***	14.761	−13.283 ***
	(4.100)	(2.184)	(1.557)	(−4.484)	(0.892)	(−4.007)
FDI	−0.851	−19.079 **	1.728	−2.638 *	−58.544	−3.890
	(−1.227)	(−3.267)	(1.315)	(−2.204)	(−1.880)	(−1.006)
LEOP	−0.132	1.986	−0.212	−0.010	9.619	−1.043
	(−1.466)	(1.311)	(−0.622)	(−0.067)	(1.191)	(−1.040)
TB	0.773	−4.654	2.080	2.029	0.331	20.041 ***
	(1.287)	(−1.290)	(1.504)	(1.958)	(0.017)	(4.925)
Province fixed effects	YES	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES	YES
Constant	9.068 ***	8.700 ***	9.295 ***	3.715 ***	−0.998	8.332 ***
	(30.315)	(6.417)	(15.566)	(7.197)	(−0.138)	(4.743)
Observations	110	66	154	110	66	154
R-squared	0.206	0.623	0.310	0.887	0.464	0.559

Note: *, **, and *** are statistically significant at 10%, 5%, and 1%, respectively. The content in parentheses is *t*-value.

5.2. Heterogeneity Analysis Based on Segmented Indicators of Digital Economy

To further analyze the specific role factors of the digital economy on the dual control of carbon emission, this paper decomposes the indicators to measure the development level of digital economic development, and divides them into four indicators, namely, digital infrastructure, digital user scale, digital industry scale, and digital innovation environment, and assigns the values to the four indicators by using the entropy method. After the above operation, the four indicators are regressed on the total carbon emission and carbon emission intensity as independent variables, and the regression results are shown in Table 9.

Table 9. Results of heterogeneity analysis based on segmented indicators of digital economy.

	CE				CI			
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
DINF	−0.674 **				−1.097 *			
	(−2.603)				(−2.298)			
DU		−0.575 ***				−2.015 ***		
		(−4.215)				(−3.941)		
DIND			−0.966 ***				−2.079 **	
			(−5.192)				(−2.897)	
DINN				−0.538 **				−1.418
				(−2.597)				(−1.822)
IS	−0.240 ***	−0.252 ***	−0.239 ***	−0.192 ***	−0.471 **	−0.604 ***	−0.494 **	−0.394 *
	(−5.465)	(−5.445)	(−5.400)	(−4.288)	(−2.752)	(−3.485)	(−2.899)	(−2.340)
UR	1.713 **	1.438 *	1.100	1.395 *	−8.053 **	−8.703 ***	−9.283 ***	−8.723 ***
	(2.746)	(2.260)	(1.740)	(2.144)	(−3.314)	(−3.646)	(−3.810)	(−3.567)
FDI	0.364	0.326	0.742	0.814	−1.451	−1.537	−0.624	−0.239
	(0.424)	(0.373)	(0.857)	(0.894)	(−0.434)	(−0.468)	(−0.187)	(−0.070)
LEOP	−0.273 *	−0.287 *	−0.397 **	−0.157	−0.060	−0.358	−0.396	0.114
	(−2.403)	(−2.421)	(−3.252)	(−1.353)	(−0.136)	(−0.804)	(−0.841)	(0.263)
TB	2.172 **	2.582 **	1.652 *	1.520	15.913 ***	17.865 ***	14.938 ***	14.470 ***
	(2.787)	(3.187)	(2.109)	(1.850)	(5.242)	(5.879)	(4.948)	(4.684)
Province fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES	YES	YES	YES
Constant	9.489 ***	9.586 ***	9.890 ***	9.627 ***	6.047 ***	6.424 ***	6.919 ***	6.431 ***
	(27.615)	(27.251)	(27.871)	(26.564)	(4.518)	(4.869)	(5.060)	(4.721)
Observations	330	330	330	330	330	330	330	330
R-squared	0.239	0.208	0.231	0.178	0.308	0.332	0.315	0.303

Note: *, **, and *** are statistically significant at 10%, 5%, and 1%, respectively. The content in parentheses is *t*-value.

The regression results show that there are significant differences in the impact of the digital economy segmented metrics on the dual control of carbon emissions. Digital user scale contributes most significantly to dual control of carbon emissions, as shown in columns (2) and (6), where the coefficients of digital user scale are both significantly negative at the 1% level; digital industry scale plays the second most significant role, as shown in columns (3) and (7), where the coefficients of digital industry scale are significantly negative at the 1% and 5% levels, respectively; the role of digital infrastructure plays the third most significant role, as shown in columns (1) and column (5), the coefficients of digital infrastructure are significantly negative at the 5% and 10% levels, respectively; the role of digital innovation environment is the least significant, as shown in columns (4) and (8), the coefficients of digital innovation environment are significantly negative at the 5% level and does not reach to be significantly negative at the 10% level, respectively. This result clearly illustrates that the positive influence of digital economy segmentation indicators on the dual control of carbon emissions is ranked as follows: digital user scale > digital industry scale > digital infrastructure > digital innovation environment. Hypothesis 4b is confirmed.

5.3. Heterogeneity Analysis Based on Property Ownership Characteristics

The results of the regressions for Model (13) are presented in Table 10. The target population is categorized into provinces with a high proportion of non-SOEs and provinces with a high proportion of SOEs according to the characteristics of property rights. Columns (1) and (2) show the moderating effect of property rights characteristics on the main effect in provinces with a higher proportion of non-SOEs, and the coefficients of the interaction terms are significantly negative at the 5% and 10% levels, respectively, which indicates that the positive effect of the digital economy on the dual control of carbon emissions is more pronounced in provinces with a higher proportion of non-SOEs. Columns (3) and (4) show the moderating effect of property rights characteristics on the main effect in provinces with a higher share of SOEs, and the coefficients of the interaction terms are not significantly negative at the 10% level, indicating that the digital economy in provinces with a larger share of SOEs does not have a positive effect on the dual control of carbon emissions. Hypothesis 4c is confirmed.

Table 10. Results of heterogeneity analysis based on segmented indicators of digital economy.

	Provinces with a Larger Proportion of Non-SOEs		**Provinces with a Larger Proportion of SOEs**	
	CE	**CI**	**CE**	**CI**
DIGE	−0.994 ***	−2.233 ***	0.020	−3.563
	(−4.043)	(−3.608)	(0.015)	(−0.625)
PC	−2.424 *	−0.106	5.258	−0.080
	(−2.263)	(−0.058)	(1.907)	(−0.011)
Interaction	−3.444 **	−5.930 *	4.311	8.499
	(−3.226)	(−2.172)	(0.537)	(0.248)
IS	−0.181 ***	−0.134	−0.367 ***	−0.827 *
	(−4.409)	(−1.397)	(−4.255)	(−2.335)
UL	0.036	−4.391 ***	1.229	−6.329
	(0.064)	(−3.311)	(1.084)	(−1.579)
FDI	0.524	−5.990 **	3.351	7.677
	(0.630)	(−2.826)	(1.835)	(1.012)
LEOP	−0.154	−0.473	−0.537	−1.450
	(−1.333)	(−1.634)	(−1.381)	(−0.880)
TB	0.740	10.276 ***	4.657 **	28.345 ***
	(0.915)	(5.036)	(2.737)	(3.996)
Constant	11.572 ***	4.269 ***	6.261 ***	5.023
	(22.884)	(4.423)	(3.573)	(1.005)
Observations	187	187	143	143
R-squared	11.572 ***	4.269 ***	0.4815	0.3712

Note: *, **, and *** are statistically significant at 10%, 5%, and 1%, respectively. The content in parentheses is *t*-value.

6. Conclusions and Policy Implications

6.1. Conclusions

In the new round of scientific and technological revolution, the digital economy has been integrated into all aspects of production and life, China, as the largest carbon-emitting country, to realize the goal of "dual carbon" as soon as possible, and to fulfill the solemn commitment to the international community, it is actively striving to achieve dual control of carbon emissions in the era of digital economy. Based on theoretical analysis and empirical tests, this paper reveals the relationship between the digital economy and the dual control of carbon emissions and draws the following conclusions:

First, the development of the digital economy in general has a positive impact on the control of total carbon emissions and carbon intensity, and this conclusion is still robust after a series of related tests.

Second, there exists a government-mediated path of environmental regulation stringency and a firm-mediated path of R&D intensity, both of which can provide a positive channel for the digital economy to drive the dual control of carbon emissions.

Third, the heterogeneity analysis from the perspective of regional development imbalance shows that there are more significant regional differences in the positive impact of the digital economy on dual control of carbon emissions, which is manifested by the fact that the positive effect is strongest in the central region, followed by the western and northeastern regions, and weakest in the eastern region. Further, the positive effects of different digital economy sub-indicators on carbon emission control also differ significantly, with the digital user scale being the strongest, the digital industry scale and digital infrastructure being the next strongest, and the digital innovation environment being the weakest.

Fourth, analyzing from the perspective of regional heterogeneity in the nature of property rights, the positive impact of the digital economy on dual control of carbon emissions in regions with a larger proportion of non-SOE is much larger than in regions with a larger proportion of SOE.

6.2. Policy Implications

Based on the above conclusions, this paper proposes the following policy implications:

First, as the positive effect of the digital economy on the dual control of carbon emissions continues to grow, governments should pay more attention to the development of environmental regulations, which require mandatory provisions but more active participation by the market and the public. It has been proved that the process of dual control of carbon emissions has been significantly accelerated after the introduction of environmental regulations such as carbon emissions trading and energy use rights trading. Therefore, under the premise of ensuring strict environmental and energy-efficiency standards, government departments should more fully utilize the market mechanism, accelerate the rule-making on various types of energy trading and the legislative process of green taxation, and encourage enterprises to reduce carbon on their own.

Second, enterprises and local governments should fully recognize the irreplaceable role of R&D in the digital economy in promoting the dual control process of carbon emissions. The 20th Party Congress clearly pointed out the need to accelerate the green transformation of the development mode. The main battlefield of the digital economy is in the enterprise, enterprises actively research and development of low-energy consumption, and high-efficiency digital products that can reduce pollution treatment costs and improve the efficiency of green production to a greater extent, in addition to releasing positive signals for external stakeholders to reduce the risk of information asymmetry. In addition, the government should also promote green investment, introduce capital into low-carbon and sustainable projects, and provide a favorable carbon reduction environment for enterprises.

Third, there are gaps in the economic base, geography, and talent pool of different regions in China, so policies should be tailored to accelerate the realization of comprehensive low-carbon and sustainable development. The eastern region should pay full attention to the problem of market saturation and fierce competition and utilize the advantages of talents and capital to realize breakthrough development through R&D and innovation. The central region, with the rapid development of the digital economy, should take full advantage of this advantage to realize the green transformation of traditional industries as soon as possible. The western and northeastern regions, as resource-based regions with relatively weak economic and R&D bases, should introduce preferential policies and provide financial support to attract more talent and funds.

Fourth, accelerate the mixed ownership reform of SOEs and actively introduce non-state capital. Mixed ownership reform of SOEs can allow SOEs to participate more deeply in market competition and improve the level of technological innovation and resource utilization efficiency of SOEs. SOEs should establish a more complete performance appraisal system, incorporating carbon emissions and green innovation into the performance appraisal, increasing enterprise vitality and promoting the process of dual control of regional carbon emissions.

6.3. Research Deficiencies and Prospects

Although this paper enters into an in-depth analysis of the relationship between the digital economy and dual control of carbon emissions, there are still some research gaps. Firstly, affected by data availability, this paper chooses provincial data as the object of empirical research on the development level of the digital economy and carbon emission dual control in different prefectures and cities of the same province may also have a large difference, to further refine the research with the enhancement of data availability. Secondly, although this paper has fully considered the relationship between the digital economy and carbon emission dual control affected by regional development imbalance, the possible spatial dependence and spatial spillover of the digital economy and carbon emission have not yet been considered in this paper, and therefore the future research will focus on expanding the analysis relying on the spatial econometric model.

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