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Environmental Protection Goes Digital: A Policy Perspective on Promoting Digitalization for Sustainable Development in China

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Abstract: In the current discourse surrounding economic and societal growth, much emphasis has been placed on the role and impact of digitalization. Despite this trend, research exploring the ecological implications of the digital economy remains scarce. To fill this research gap, our study aimed to investigate the correlation between the digital economy and carbon emissions, specifically examining the moderating impact of environmental regulations. For empirical analysis, we utilize the CRITIC methodology to establish a thorough set of indicators that can evaluate the performance of China's digital economy. According to our empirical results, the digital economy seems to exert a moderating influence on the levels of carbon dioxide (CO_2) emissions, and this negative impact is more pronounced in affluent and densely populated regions of China. The effectiveness of digitalization in reducing pollution can be enhanced by the enforcement of environmental regulations. This paper elucidates the potential mechanisms via which the digital economy affects carbon dioxide emissions, and constructs a framework for the mechanisms via which the digital economy affects the environment by influencing the carbon dioxide emissions, providing a new way for enterprises and governments to participate in environmental protection and expanding the content of research related to the digital economy.

Keywords: digital economy; carbon emissions; environmental regulations; air pollution; climate change

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1. Introduction

Over the past few decades, the impact of the digital economy has permeated various socioeconomic domains, affecting an array of areas including communication modalities, production methods, and entrepreneurial frameworks. Specifically, digital technologies reduce transaction costs by providing more accessible communications, advance the manufacturing sector with a more productive and more ecological sustainable production [1], and reallocate financial resources for boosting financial inclusion [2]. Hence, the transformation and evolution of digital technologies have become crucial for industrialization, ultimately influencing the economy and the environment [3,4]. There is considerable optimism that the digital economy can play a vital role in addressing climate change and associated environmental challenges. The integration of digital technologies into the design of smart cities, transportation networks, industrial processes, and energy conservation initiatives is anticipated to lead to a substantial reduction in carbon dioxide emissions [5]. However, some lines of argument indicate that digitalization is more detrimental than beneficial to the environment [6]. This concern mainly stems from the rising energy consumption in the production and disposal of digital facilities, which may partly or wholly offset the potential capabilities of environmental protection [7]. As a result, a wide variety of arguments have investigated whether the digital economy can improve or worsen environmental performance [8].

Climate change is now a global menace, along with sea-level rise, wildfire outbreaks, and extreme weather. The severe situations beyond the national borders require all the countries to be more responsive to environmental issues. Any attempt to tackle these challenging issues focuses on reducing greenhouse gas emissions, especially CO_2 emissions [9]. The emission of digital-related pollutants in developing countries is attributable, in part, to the employment of low-level skills and technologies in waste management [10]. On the contrary, the majority of preceding research regarding the influence of digitalization on productivity at the national level has uncovered that digital technologies exhibit a more pronounced and favorable impact on efficiency in developed nations, as compared to their developing counterparts.

China, as the largest developing nation and a substantial manufacturing hub, has been struggling with a mounting environmental burden caused by elevated levels of energy consumption and subpar energy efficiency [11]. In the current era of digitalization, the fusion of technology and environmental preservation has emerged as a pivotal goal in the pursuit of China's high-quality development. Accordingly, the Chinese government has implemented a bunch of initiatives (e.g., "Digital China" and "Broadband China" strategies) to boost digital development. With regard to the 2020 White Paper on the Development of China's Digital Economy released by the China Academy of Information and Communications Technology (CAICT), China's digital economy reached a total of 6.28 trillion USD in the same year, representing 38.6% of the national GDP. Undoubtedly, advanced technological solutions in industries and financial sectors wield significant impact in propelling economic growth and mitigating ecological footprints. As depicted in Figure 1, the trends of carbon dioxide emissions and the digital economy from 2012 to 2017 are apparently intertwined in China. The graph shows an overall decreasing trend in CO_2 intensity with the development of the digital economy. However, as the digital economy continued to grow, the decline in CO_2 intensity between 2015 and 2017 was not significant. Therefore, evaluating the potential benefits of digitalization for developing countries has emerged as a critical imperative.

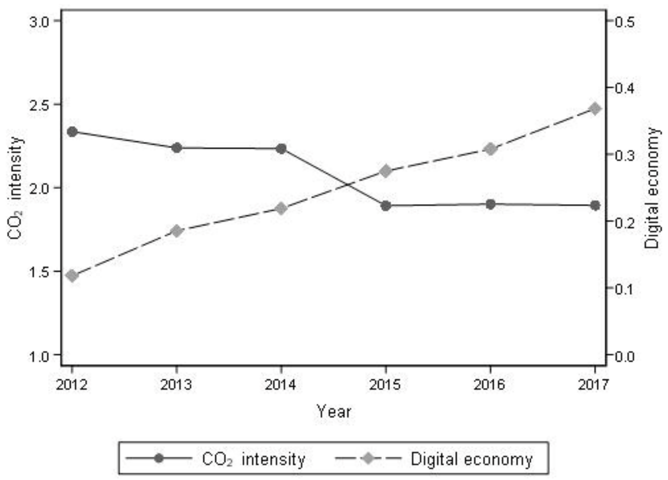

Figure 1. Time series plot of the digital economy and CO_2 intensity, 2012–2017.

As a result, it prompts the inquiry of how to optimize the efficacy of digital technologies as a driving force for resource utilization efficiency and industrial pollution mitigation. The increasing adoption of digital technologies coordinated with effective environmental regulations can be a vital catalyst for mitigating climate change and reshaping carbon abatement tactics. Asymmetrical information is one of the possible causes of ecological straits, exacerbates the financial burden of environmental preservation, and undermines the efficacy of environmental law enforcement [12]. The interaction, intelligence, and instantaneity of digital technologies can mitigate asymmetrical information, effectively solving and preventing pollution events. Environmental authorities can employ digital facilities to monitor polluted firms in real time and adopt stricter penalties for environmental damages [13]. Moreover, digital facilities (e.g., the Internet and mobile phones) facilitate the public's engagement in supervising and reporting environmentally damaging practices to the government. This serves as a way to address certain shortcomings of traditional environmental regulations. These considerations establish the framework for analyzing the interdependent connection among the digital economy, ecological criteria, and carbon dioxide emissions.

On the basis of our earlier discussion, it seems that the effects of the impact of the digital economy on the environment are somewhat equivocal. Additionally, the intricate nature of digitalization exhibits similarities across both developed and developing nations. Furthermore, while the digital economy and environmental regulations could have a significant influence on carbon dioxide emissions, the level of interdependence and the connection among these components remain relatively limited. Hence, it is worth exploring profound evidence on the digital economy, environmental regulations, and other determinants of carbon emissions in developing countries. Building on the aforementioned arguments, the present study explores the interplay between the digital economy and environmental regulations, as well as other pertinent independent variables such as the industrial structure, GDP per capita, number of patents, and population intensity, with regard to their impact on CO_2 emissions. In order to achieve this objective, we first utilize the CRITIC methodology to develop a comprehensive set of indicators to assess the performance of the digital economy in China. This paper uses a fixed-effect model and an instrumental variable estimation model to test the impact of the digital economy on carbon emissions. This method can successfully achieve the estimation goal of this paper. Firstly, the fixed-effect model, as the main method to deal with endogeneity, can adequately identify the causal effect of the digital economy on carbon emissions; combined with instrumental variable estimation regression, it can further identify the impact of the digital economy on carbon emissions. Secondly, due to the fact that the digital economy can only be measured at the provincial level, fixed-effect models can differentiate the impact of unobservable macro factors on carbon emissions at the provincial level, thereby better identifying the impact of the digital economy on carbon emissions. Lastly, some relevant studies have adopted similar methods, which better demonstrates the effectiveness of this method and provides further evidence for the use of this method in this article.

Subsequently, we examine the correlation between the digital economy and the emissions of carbon dioxide (CO_2) over the period spanning from 2012 to 2017. This study employs an instrumental variable methodology to ascertain the impact of the digital economy on carbon dioxide emissions, utilizing the exogenous variability in historical access to postal and telecommunications services as an instrument for measurement. We perform a series of heterogeneity analyses by geographical regions and their population characteristics, and then indicate how results can vary across these dimensions. Our research team conducted an investigation that centers around the regulatory framework needed to moderate the impact of the digital economy on the environment. This study also incorporates a careful examination of macrolevel processes, including technological innovation and industrial organization. Our empirical research provides strong evidence supporting the proposed mechanisms. The findings of our investigation suggest that (i) the digitalization of the economy has a substantial and enduring impact on the reduction in carbon dioxide emissions, (ii) various tests examining heterogeneity reveal that the effects of digitalization are particularly pronounced and efficacious in densely populated and prosperous regions of China, and (iii) incorporating digitalization into environmental policies yields favorable regulatory outcomes at the interface between the digital economy and carbon emissions reduction.

There are three possible contributions of this paper to the literature. (i) Many people believe that business development can cause damage to the environment. The reason is that enterprises may neglect environmental protection in pursuit of profits, and cause massive resource consumption and pollution emissions in the process of enterprise production, resulting in the incompatibility between enterprise development and environmental protection objectives. This paper builds a new theoretical framework on the impact of the digital economy on the CO_2 intensity of enterprises, which provides a new path for enterprises and governments to participate in environmental protection. (ii) This paper finds that environmental regulations also have a positive moderating effect on the CO_2 intensity of the digital economy on businesses, enriching existing research on areas related to the impact on carbon emissions intensity. (iii) The results have significant policy implications for mitigating the environmental ramifications of the expanding digital economy, providing valuable insights for policymakers and stakeholders alike, which can help Chinese policymakers effectively plan future environmental regulations, as well as offer guidance to policymakers in other developing countries.

The remainder of this document is structured as follows: Section 2 engages with an in-depth review and analysis of the existing literature regarding the subject matter; Section 3 outlines the intricacies of our research methodology and the nature of the data gathered; Section 4 showcases the empirical findings that were derived through our inquiry; Section 5 offers a summation of our research findings, accompanied by policy implications.

2. Literature Review

The digital economy is characterized by the utilization of digital knowledge and information as essential components of production, facilitated by advanced information networks. Accordingly, investigations into the influence of digital technologies on carbon dioxide emissions can furnish valuable insights. A pertinent area of inquiry pertains to the nexus between the digital economy and environmental considerations. However, the digital economy's beneficial and detrimental environmental implications have been widely debated for the past decade, without reaching a consensus.

First, some scholars have concluded that the deployment of digital technologies in various sectors of the economy can lead to potential pollution reduction and energy conservation. The study found that the digital economy has a catalytic effect on the level of total factor carbon production in China, with significant regional heterogeneity, and it can be one of the important ways to improve the level of green development [14]. Digital technologies are related to creating a cleaner and more environmentally sustainable production process. The "Broadband China" pilot policy, as a quasi-natural experiment, found that network infrastructure construction can reduce environmental pollution through the double difference method [15]. The authors pointed out that the application of image recognition technology to environmental pollution detection can effectively improve detection efficiency and accuracy [16]. Salahuddin, Alam, and Sadorsky [17] conducted a research study examining the impact of labor-saving machines on CO_2 emissions reduction compared to the utilization of labor-intensive production processes and mechanization. Their findings suggest that the implementation of labor-saving machinery is a more promising approach to reducing CO_2 emissions. The second viewpoint suggests that the growing production, utilization, and disposal of digitalization have adverse environmental impacts and stimulate polluting emissions and wastes [18]. In addition to the adverse effects on CO_2 emissions, digital technologies could increase energy consumption by producing digital facilities and running the infrastructure. Research conducted recently indicates that there exists an inverted U-shaped correlation describing the effects of digital technologies on carbon dioxide emissions. That is, the environmental quality becomes worse in the early stage of digitalization; however, pollution is reduced along with thriving digitalization [19,20]. Some scholars also argued that the relationship between digitalization and the environment is theoretically ambiguous and worth further analysis [19]. To steer digitalization toward a sustainable direction, it is crucial to take into account the diverse impacts it has, as highlighted by Pamlin in 2002.

Furthermore, another corpus of the literature has highlighted the influence of the digital economy on the environment, emphasizing that digitalization alone is inadequate in decreasing harmful emissions. Specifically, digital technologies have reduced the world-wide outdoor activities and freightage (e.g., teleworking, online meetings, and e-commerce), thus diminishing fuel consumption and greenhouse gas emissions. With the development of the digital economy, the impact of the coal-based energy structure on carbon emissions is gradually decreasing [21]. Furthermore, the digital economy can reduce transaction costs and reallocate resources through more accessible communication tools that help mitigate carbon emissions (e.g., online business, inclusive finance, and sharing economy). Furthermore, digitalization allows for faster diffusion of information, leading to innovations in the energy and technology sectors. These innovations are conducive to optimizing production processes, transforming and upgrading the manufacturing industry, and ultimately reducing pollutants [5]. Digital facilities (e.g., the Internet and mobile phones) allow for rapid dissemination of knowledge and awareness pertaining to education and training in the field of environmental management, contributing to enhanced environmental awareness and pro-environmental behavior of the public. Lastly, the new-generation digital technologies, especially big data and artificial intelligence (AI), have higher sensitivity, adaptability, and linkage, and are practical implementations for government environmental detection.

After examining the discourse on the topic, it is evident that the correlation between the digital economy and the environment has been a topic of continuous discourse for a number of decades. Multiple studies have highlighted the potential for reducing CO_2 emissions through information dissemination, technological advancements, and decreased transaction costs [22]. Existing articles on the impact of the digital economy on CO_2 emissions intensity have mainly used OLS models with mediating effects models to estimate the digital economy on carbon emissions [23], while some studies have also found a positive moderating effect of R&D investment on the digital economy on CO_2 emissions intensity [24]. One study measured comprehensive indicators of the level of development of the digital economy by constructing a system of indicators using the entropy value method and found that, with the development of the digital economy, more and more cities are shifting to low-carbon development. The downside is that the data obtained by the crawler on the frequency of digital words in listed companies may not be pure enough [25]. Digital technology has varying impacts on CO_2 emissions across different economic sectors. However, the previous literature has neglected to analyze the influence of environmental regulations.

Therefore, there is a necessity to enhance comprehension regarding the impact of the digital economy and environmental regulations on carbon dioxide emissions. This represents the innovation of this article, which endeavors to bridge this research void.

3. Empirical Methodology

3.1. The Model

The empirical research demonstrates a connection between carbon dioxide emissions and the digital economy, while considering environmental standards. Initially, in order to assess the influence of the digital economy on CO_2 emissions, the econometric model employed in this inquiry is represented by Equation (1).

$$CO_{2it} = \beta_1 DE_{jt} + \beta_k Control_{it} + \lambda_i + \gamma_t + \varepsilon_{it}, \quad (1)$$

where the indices i, j, and t correspond to the urban center, administrative region, and time period, respectively. We assume that CO_2 emissions (CO_{2it}) depend on the digital economy index (DE_{jt}) and a vector of other covariates (Controlit). Additionally, λ_i represents city fixed effects that acquire stable and unchanging urban features that cannot be directly observed, while γ_t represents year fixed effects, and ε_{it} is the stochastic error term. Our coefficient of interest is β_1, indicating a $100 \times \beta_1$ decrease in the CO_2 intensity due to an additional unit of the digital economy.

Moreover, a supplementary corpus of the literature has underscored the influence of the digital economy on the environment, emphasizing that digitalization alone is inadequate in decreasing harmful emissions. The moderator variables, i.e., environmental regulations (M_{jt}), are added into the model, as they may mitigate the CO_2 emissions.

$$CO_{2it} = \theta_1 DE_{jt} + \theta_k M_{jt} + \lambda_i + \gamma_t + \varepsilon_{it}. \quad (2)$$

Equation (3) is a development of Equation (2) that encompasses the integration of the interplay between the digital economy and environmental standards ($DE_{jt} \times M_{jt}$) into the model.

$$CO_{2it} = \vartheta_1 DE_{jt} + \vartheta_k M_{jt} + \vartheta'_k DE_{jt} \times M_{jt} + \lambda_i + \gamma_t + \varepsilon_{it}. \quad (3)$$

The variable M_{jt} is employed as a moderator that encompasses three distinct factors: the number of environmental legislations per capita (law), the frequency of environmental penalties per capita (penalty), and the volume of environmental department personnel per capita (employee).

3.2. Data and Variables

The dataset utilized in the investigation encompassed 31 provinces and significant prefecture-level urban municipalities located in mainland China, from 2012 to 2017. The compilation of data at the provincial level mainly relied on the Statistical Yearbook of China, while data at the city level were derived from the corresponding City Statistical Yearbooks.

Currently, the measure of the digital economy is somewhat mixed as the definition is not uniform across countries. The fundamental interrelationship between digitalization and carbon dioxide emissions has been the subject of extensive scholarly inquiry, where ICT has frequently been employed as a surrogate for digitalization. Some indicators (e.g., the number of netizens, fixed telephone subscribers, or websites) are selected for their measurable and all-pervading nature [8]. Undoubtedly, the advances in digital infrastructure have become increasingly essential to the economy, society, and daily life of people worldwide. As a proxy for digitalization, digital infrastructure represents the accessibility of digital technologies for households and production use. Moreover, digital transactions have changed the economic operation fundamentally as the monetary proxies for the digital economy, which in turn impacts the environment somehow. Subsequently, we include digital infrastructure transactions in the composite digital economy index [18,26]. Indicators measuring digital infrastructure in this study include the density of optical cables and mobile phone base stations, broadband Internet subscribers per 100 inhabitants, and mobile phone users per 100 inhabitants. In addition, we incorporate fundamental trade features, such as the proportion of businesses utilizing computers and the volume of E-commerce sales, as metrics for digital transactions. The composite index is expected to help account for the development of digitalization and digital transactions, as well as access to digital services. We compiled data on digital infrastructure and digital transactions from authoritative sources such as the National Bureau of Statistics of China and the Statistical Yearbook of China (2012–2017).

Prior to conducting the econometric analysis, we utilized the CRITIC methodology to determine the weighting scheme for constructing a composite index of the digital economy. The weight matrix can be presented as follows:

$$w_i = \frac{C_i}{\sum_j^n C_j}, \; i = 1, 2, \ldots, n, \quad (4)$$

where $C_i = \sigma_i i \sum_j^n (1 - r_{ij})$, i = 1, 2, ... , n ($i \neq j$), σ_i is the standard deviation of index i, and r_{ij} is the correlation coefficient between index i and index j.

Among the numerous environmental risks, the escalating levels of carbon dioxide emissions, which currently stand at record highs, are commonly recognized as the primary instigator of climate change concerns [9]. Hence, we chose CO_2 emissions as a proxy for environmental pollution. The Ministry of Ecology and Environment of China aggregates metrics pertaining to the response variable representing CO_2 emissions, which are quantified in terms of metric tons per individual. In order to depict the visual progress of our crucial parameters, we charted the CO_2 intensity against various levels of the digital economy in Figure 2. As depicted in Figure 2, the CO_2 intensity showcases a noteworthy and consistent decline, concomitant with the flourishing of the digital economy.

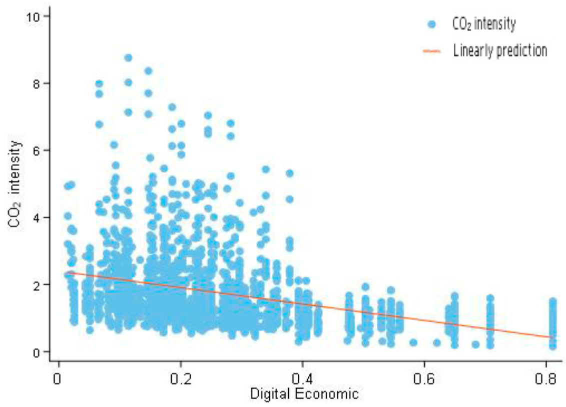

Figure 2. Scatter diagram of the digital economy and CO_2 intensity.

Other variables considered as potential determinants of CO_2 emissions in this study, as recommended by the prior literature, included gross domestic product (GDP) per capita [27], population intensity, foreign direct investment (FDI), industry structure, and patents per capita. In accordance with the widely accepted paradigm of the nexus between economic growth and the environment, the environmental Kuznets curve (EKC) framework posits that pollutant emissions are expected to escalate in tandem with the gross domestic product (GDP) until a certain threshold is reached, after which further economic growth leads to the mitigation of pollutants [28,29]. Previous studies have confirmed that innovations, especially patents related to energy and technology sectors, are conducive to economic prosperity and carbon reduction in the long run [12]. Data on patents were derived from the China Intellectual Property Office.

The variables employed are summarized in Table 1.

Table 1. Variable summary statistics.

Variable	Definition	Obs	Mean	Std. Dev.	Min	Max
CO_2 emissions (CO_2)	Carbon emissions (metric tons per capita in log)	1716	1.758	1.121	0.156	8.757
Digital economy (DE)	The digital economy indicator (log)	1716	0.262	0.160	0.015	0.811
GDP per capita (GDP)	GDP divided by the population at the end of the year (10,000 CNY per capita in log)	1716	5.037	3.008	0.816	21.549
Population	Population size (person in log)	1716	8.185	0.694	5.288	10.432
FDI (FDI)	Foreign direct investment (log)	1716	5.259	2.377	−21.263	10.099
Industry structure	The tertiary-to-secondary industry output ratio	1716	1.950	1.714	0.250	6.726
Patents	The number of patents per capita (log)	1716	1.705	1.324	−2.537	5.918

OLS estimates of the association between the digital economy and CO_2 emissions are susceptible to bias; CO_2 emissions are not randomly assigned but affected by a bunch of socioeconomic and institutional factors that even the most sufficient controls might fail to account for fully. For one thing, with numerous drivers of CO_2 emissions, possible endogeneity concerns arise due to the potential omitted variables.

4. Empirical Results and Analysis

4.1. Baseline Finding

In our analytical models, we employ diverse methodological approaches to evaluate the impact of the digital economy on carbon dioxide emissions. The results are presented in Table 2. The estimates for Equation (1) using fixed-effects models are reported in columns (1)–(3). The results show that the development of the digital economy reduces CO_2 emissions, and the results are all significant at the 1% level. Furthermore, we employed the instrumental variable (IV) approach to address any potential endogeneity concerns in our analysis, and the findings from the two-stage least squares (2SLS) model are reported in columns (4) and (5) of our regression output. Specifically, with regard to our main explanatory variable (Digital), both the linear regression results and the 2SLS estimates demonstrate a strong and statistically significant negative relationship (significant at the 1% level) between the digital economy and CO_2 emissions reduction. This compelling evidence signifies that the growth of the digital economy plays a substantial role in promoting environmental sustainability. There are two possible reasons. For one thing, digital applications can stimulate traditional industries to achieve a higher efficient production process, resulting in energy conservation. For another, digital technologies support the development of environmental online auto-monitoring systems and help the environmental department crackdown on illegal activities that are detrimental to the environment. Thus, the digital economy facilitates the transition of industries and fosters a more sustainable, low-carbon economy. This finding may inspire policymakers to continuously stimulate the digitalization progress to inject new vitality into environmental protection.

Table 2. OLS and IV estimates of the impact of the digital economy on CO_2 emissions.

	(1)	(2)	(3)	(4)	(5)
		FE		IV	
lnDigital	−0.191 ***	−0.242 ***	−0.167 ***	−0.174 **	−0.230 **
	(0.066)	(0.056)	(0.060)	(0.079)	(0.100)
lnGDP		−0.129 ***	−0.088 ***		−0.088 ***
		(0.014)	(0.018)		(0.019)
lnPopulation		−0.292 ***	−0.209 ***		−0.209 ***
		(0.065)	(0.064)		(0.064)
lnFDI			−0.069 ***		−0.068 ***
			(0.022)		(0.023)
Industry			−0.030		−0.030
			(0.019)		(0.019)
lnPatent			−0.068		−0.066
			(0.045)		(0.045)
N	1716	1716	1716	1716	1716
R-squared	0.655	0.736	0.748	0.003	0.271
idstat				53.864	53.701
cdf				132.420	125.638
rkf				16.466	15.920

Note: All regressions incorporate fixed effects for both province and year, as well as control for city-specific characteristics. Standard errors are robust and clustered at the provincial level, with statistical significance levels denoted by **, and *** for 5%, and 1%, respectively. The under-identification test is represented by idstat, while cdf and rkf stand for weak identification tests using the Cragg–Donald Wald F statistic and Kleibergen–Paap rk Wald F statistic, respectively.

Our assessments of the digital economy are susceptible to measurement errors, which could potentially skew the ordinary least squares (OLS) estimate of the treatment effect toward zero. Nonetheless, in columns (3) and (5), the results from estimating the instrumental variables (IVs) indicate a larger estimate than the OLS estimate, given that the measurement error does not affect the former method. Additionally, the outcomes of the first-stage estimation provide further evidence that there is no bias resulting from weak instruments. Taken together, having taken into account the potential endogeneity issues, the analysis demonstrates that our findings are reliable and impactful, which is evident from the results presented in Table 2.

Regarding other control variables, there is a difference in the magnitude of the coefficients between the IV and OLS estimates in Table 2, while the sign and significance are consistent. We find that the coefficients on GDP, population, and FDI are significantly negative, and all results are significant at the 1% level. The findings indicate that the digital economy, coupled with a burgeoning economic expansion, massive population resources, and extensive foreign direct investment, can be instrumental in reducing CO_2 emissions. Moreover, the adverse impact of patents on carbon dioxide emissions is not a significant contributing factor, which implies that improving the quality of innovation is more imperative than increasing the number of patents. We also find that industrial structure causes a decline in CO_2 emissions, but this finding lacks statistical significance.

4.2. Heterogeneity Test

Since China has a vast territory, the development and resource endowments of different region in China is rather heterogeneous. In order to address unidentified local variations in the digital economy and carbon emissions, we opted to amalgamate individual cells into discrete geographical zones. Table 3 demonstrates the regional heterogeneity of the impact of the digital economy on CO_2 emissions throughout the country. As can be seen from the results in the table, the impact of the digital economy on CO_2 emissions shows regional heterogeneity, with negative results for the eastern and western regions, significant at the 1% and 5% levels, respectively. Notably, the findings in columns (1) and (3) reveal that the digital economy plays a decisive role in diminishing CO_2 emissions in both the eastern and western regions, although the former yields a more pronounced reduction compared to the latter. The sample included 11 provinces and municipalities in eastern China (e.g., Beijing, Shanghai, Jiangsu, Guangdong, and Zhejiang), eight in central China (e.g., Henan, Hubei, and Shanxi), and 12 in western China (e.g., Chongqing, Sichuan, Shaanxi, and Yunnan). Xinjiang and Tibet were excluded from the sample due to data limitations. The eastern region has the most extensive scale of digitalization in China. Interestingly, the coefficient in column (2) is significantly positive, which indicates that CO_2 emissions will increase with the digital economy's prosperity. It seems possible that the massive production, use, and disposal of digital facilities might be the cause of growing CO_2 emissions. Likewise, the effects of the digital economy on carbon dioxide emissions exhibit a considerably adverse impact in the southern parts of China, while the impact is negligible and positive in the northern region. China is roughly divided into two parts (i.e., the north and the south), along the Qinling Mountains–Huaihe River line. Representative provinces in the north include Beijing, Hebei, Jilin, Liaoning, and Shandong. Representative provinces in the south include Shanghai, Shenzhen, Jiangsu, and Zhejiang. Generally, the south region is more developed than the north region in economic development and environmental management; the north is mostly an industrially developed region where more pollutants are discharged. Our findings also reveal heterogeneity in the relationship between the digital economy and CO_2 emissions across areas with different population sizes. Specifically, we observe a statistically significant association between the digital economy and CO_2 emissions at a confidence level of 1% in regions characterized by a medium-to-large population scale. However, in small-scale regions, the digital coefficient is statistically insignificant. A possible explanation for the negligible role of small-scale regions in CO_2 emissions reduction may lie in that, with urbanization and industrialization, regions with a smaller population are gradually falling behind developed areas, where the benefits of digitalization are also under restrictions.

Table 3. Regional and scale-related differences in the impact of the digital economy on CO_2 emissions.

	Regional Differences					**Scale-Related Differences**		
	Eastern China (1)	**Central China (2)**	**Western China (3)**	**Northern China (4)**	**Southern China (5)**	**Small-Scale (6)**	**Medium-Scale (7)**	**Large-Scale (8)**
Digital	−0.695 ***	0.284 ***	−0.287 **	0.119	−0.230 ***	−0.059	−0.403 ***	−0.192 ***
	(0.182)	(0.092)	(0.113)	(0.239)	(0.056)	(0.097)	(0.111)	(0.061)
N	606	606	504	714	1002	572	571	571
r2	0.749	0.713	0.757	0.743	0.676	0.788	0.766	0.757

Notes: Standard errors are robust and clustered at the provincial level, with statistical significance levels denoted by **, and *** for 5%, and 1%, respectively. The regression model incorporates fixed effects for each province and year, while also including the standard control variables. Standard errors are presented in parentheses and clustered by province for improved accuracy.

4.3. Moderating Effect of Environmental Regulations

The aforementioned segment illustrated that the digital economy has a beneficial effect on mitigating carbon dioxide emissions. In this section, we examine whether this effect acts through the channel of environmental regulations. As environmental regulations may positively impact mitigating CO_2 emissions, we anticipate a substantial moderating influence of environmental regulations on the ability of the digital economy to attenuate carbon emissions. The outcomes are presented in Table 4, where the coefficients on the interaction terms analyzed (digital × law and digital × penalty) are significant at the 1% level, with the same sign as the standalone digital coefficient, as shown in columns (1)–(2). On the basis of our research, it is apparent that environmental regulations, specifically environmental laws and penalizations, can have a salutary influence on the ecological consequences of the digital economy. This substantiates our argument that the digital economy can mitigate CO_2 emissions through strict adherence to environmental regulations. A well-established environmental regulation system can efficiently supervise firms' production and environmental management practices, thus restricting the level of pollution emissions. The digital coefficient is not significant, as shown in column (3), indicating that the environmental department would be tedious with manifold personnel and require a highly skilled staff composition to ensure that the environmental protection policies were implemented correctly.

Table 4. Moderating effects of environmental regulations.

	(1)	**(2)**	**(3)**
Digital	−0.127 **	−0.279 ***	−0.080
	(0.061)	(0.074)	(0.067)
Digital × law	−0.485 **		
	(0.234)		
Law	1.172 ***		
	(0.420)		
Digital × penalty		−0.055 **	
		(0.024)	
Penalty		−0.114 ***	
		(0.031)	
Digital × employee			−0.134 ***
			(0.036)
Employee			0.604 ***
			(0.183)
N	1716	1716	1716
R-squared	0.753	0.754	0.760
Digital	−0.127 **	−0.279 ***	−0.080
	(0.061)	(0.074)	(0.067)

Note: In our regression analysis, the independent variables "law", "penalty", and "employee" represent the per million people figures for environmental legislations, administrative penalty cases, and environmental department personnel, respectively. Our model includes fixed effects for both province and year, and controls for various factors, such as population scale, FDI, GDP per capita, industrial structure, and patents per capita. The reported standard errors (in parentheses) are clustered at the province level, and significance levels are indicated by **, and *** for 5%, and 1%, respectively.

Furthermore, we examined the variations in the moderating impacts of the interplay between the digital economy and carbon dioxide emissions across various regions with respect to the impact imposed by environmental regulations. Table 5 presents the estimated outcomes; as evidenced in columns (1)–(3), we observe insignificant coefficients on the digital × law interaction term, suggesting that environmental legislations have a feeble deterrent effect on illegal activities detrimental to the environment. With regard to the moderating influence of environmental penalties, there is significant disparity across the eastern, central, and western regions, as evidenced by the significant differences illustrated in columns (4)–(6). In eastern and western areas, coefficients on the digital × penalty interaction term are significantly negative, indicating that the imposition of environmental penalties exacerbates the adverse effects of the digital economy on the level of CO_2 emissions. However, both the standalone digital and the digital × penalty interaction term coefficients are positive and insignificant, as shown in column (6). The possible reasons are that, in contrast to central regions, the eastern region exhibits a greater degree of economic advancement and environmental enforcement levels while the western region naturally has lower CO_2 emissions due to the less developed industry and sparse population. However, the digital and digital × empolyee interaction term coefficients are insignificant in columns (7)–(9), indicating that the moderating influence of environmental regulatory personnel did not exhibit a statistically significant effect on the capacity of the digital economy to mitigate carbon dioxide emissions. In summary, our findings indicate that environmental regulations can strengthen the contribution of digitalization to reducing potential pollutant emissions in developed regions. This offers a suggestion to accelerate the growth of the digital economy in emerging regions.

Table 5. Regional heterogeneity: moderating effect of environmental regulations.

	Environmental Legislation			**Environmental Penalties**			**Environmental Department Personnel**		
	(1) **Eastern China**	**(2)** **Central China**	**(3)** **Western China**	**(4)** **Eastern China**	**(5)** **Central China**	**(6)** **Western China**	**(7)** **Eastern China**	**(8)** **Central China**	**(9)** **Western China**
Digital	−0.863 ***	0.417 ***	−0.309 **	−0.763 ***	0.115	−0.567 ***	−0.284	0.271 ***	−0.257 **
	(0.229)	(0.120)	(0.129)	(0.202)	(0.102)	(0.132)	(0.191)	(0.099)	(0.116)
Digital × law	−1.403	0.550	0.355						
	(0.889)	(0.552)	(0.407)						
Law	1.620 *	2.405 **	1.894						
	(0.966)	(0.961)	(1.202)						
Digital × penalty				−0.129 ***	0.012	−0.127 **			
				(0.049)	(0.032)	(0.050)			
Penalty				−0.001	−0.120 ***	−0.073			
				(0.054)	(0.043)	(0.088)			
Digital × employee							−0.258 ***	−0.056	−0.016
							(0.089)	(0.052)	(0.071)
Employee							0.959 ***	0.913 ***	0.316
							(0.243)	(0.278)	(0.467)
N	707	707	588	707	707	588	707	707	588
R-squared	0.883	0.806	0.822	0.885	0.813	0.818	0.891	0.826	0.816

Note: The regression analysis takes into account the fixed effects for both province and year, and the reported standard errors are clustered at the provincial level. Results with statistical significance are denoted with asterisks (* $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$). Furthermore, the usual controls are incorporated. Overall, this model provides a rigorous and sophisticated approach to understanding the dynamics among environmental regulations, digital economy, and carbon emissions across different regions.

The digital revolution has a close relationship with both the informatization of the environmental regulatory system and the public's involvement in environmental protection. In other words, the increasing maturity of digital technologies has reinforced the abilities and chances of environmental information acquisition, flow, and use. Hence, the public and organizations concerned about the environment can widely access and apply relevant knowledge and information through digital facilities. For one thing, digital technologies (e.g., big data and cloud computing) have also enriched the means of environmental monitoring, such as real-time dynamic monitoring of environmental information including air quality, river water quality, and soil changes. Digitalization enables efficient deployment of various resources and facilitates sharing of environmental information among departments; in doing so, policymakers are able to overcome the shortcomings of conventional regulatory instruments and augment the potency of environmental compliance measures [30,31]. Additionally, the diffusion of digital technologies is likely to trigger people's concern about ambient environmental pollution. For instance, the public can submit illegal activities detrimental to the environment by using mobile terminal platforms and supervising the departments to actively follow up and resolve such pollution issues. Hence, we conduct supplementary analyses to acquire a more comprehensive comprehension of the impacts of the digital economy on both individualistic and governmental conducts.

Table 6 exhibits a significant and advantageous influence of the digital economy on two crucial factors: the number of environmental-related telephone complaints and the adoption of auto-monitoring systems by firms or cyber-firms. The findings indicate that the digital economy has a beneficial effect on individuals. and governmental behaviors. Specifically, in column (1), the digital coefficient is significantly positive, indicating that the public can deliver environmental information using real-time digital communication technologies. Public participation in environmental protection and reporting environmental violations indirectly serves as a monitoring function to strengthen environmental regulations. Compared with the results in column (2), the digital coefficient in column (3) is more significant (significance at the 1% level), suggesting that the digitization of environmental monitoring enhances the tools available for environmental regulation and increases the efficiency and efficacy of environmental law enforcement. Once the information about polluting firms is networked, it will constitute a specific deterrent effect on emission behaviors and urge firms to reduce pollutant discharge. Moreover, digitalization allows the environmental department to be more quickly informed about and handle sudden environmental pollution emergencies. As a result, it is imperative for the government to disseminate information about environmental regulations and knowledge, and to enable effective public oversight of activities that violate environmental laws and regulations.

Table 6. The influence of the digital economy on the conduct of individuals and government entities.

	(1)	(2)	(3)
	Telephone Complaints Related to Environmental Issues	**Firms with Auto-Monitoring System**	**Cyber-Firms with Auto-Monitoring System**
Digital	1.688 **	0.022 **	0.028 ***
	(0.746)	(0.009)	(0.010)
N	210	210	210
R-squared	0.198	0.251	0.296

Note: The reported standard errors (in parentheses) take into account clustering at the provincial level. Statistical significance is indicated by asterisks (**, and *** denote significance at the 5%, and 1% levels, respectively). To account for variations in population scale and fiscal expenditure, we utilize panel data at the provincial level.

Our benchmark models (see Table 2) account for the effects of the patents and industrial structure on CO_2 emissions. The estimations so far have served to identify the negative impacts on CO_2 emissions; however, the estimated coefficients are not significant. Hence, we divided the panel data into groups to exploit the determinant mechanism of CO_2 emissions regarding the different degrees of innovation and industrial structure. Notably, we calculate the industrial structure using Equation (5).

$$IS_{it} = \sum_{m=1}^{3} y_{i,m,t} \times lp_{i,m,t}, m = 1, 2, 3, \tag{5}$$

where IS_{it} denotes the industrial structure in region i at time t, and $y_{i,m,t}$ is the share of industry m of region i in GDP at time t. The index provides insight into the transition of China's economy from a primary industry-dominated to a secondary and tertiary industry-dominated one, as it tracks the proportional relationship among these three major industries over time.

Furthermore, $lp_{i,m,t}$ is the labor productivity of industry m, expressed as Equation (6).

$$lp_{i,m,t} = \frac{Y_{i,m,t}}{L_{i,m,t}}, \quad (6)$$

where $Y_{I,m,t}$ denotes the value added of industry m in region i at time t, and $L_{i,m,t}$ denotes the employment of industry m in region i at time t.

Ordinarily, the effect of technological advances on the environment covers the whole process of pollution precaution, management, and reduction. Efficient and environmentally friendly production technologies can effectively mitigate the emission of pollutants. However, technological innovations may just expand the scale of production rather than environmentally benign manufacturing when innovations have exacerbated environmental pollution. The industrial structure represents another mechanism that contributes to the ecological ramifications of the digital economy. With the economic system transformed from agriculture to industry, in the initial phase of economic growth, the accelerated industrialization led to excessive consumption of resources and a significant increase in waste emissions, resulting in the deterioration of environmental pollution. Subsequently, the industrial structure was optimized and upgraded; that is, the percentage of industries with high energy consumption and pollution levels declined, whereas the proportion of tertiary industries increased. When compared to the primary and secondary sectors, the tertiary sector demonstrates lower resource consumption and reduced discharge of pollutants, thereby suggesting a positive correlation between a higher proportion of tertiary industry and diminished levels of pollution.

The tabulated outcomes are recorded in Table 7. According to columns (1) and (4), it can be observed that the estimated regression coefficients for the digital variable are positively signed and significant at the 10% levels, suggesting that digitalization provides enterprises with opportunities to access information about innovation and develop clean production methods. Innovation has enabled traditional industries to shift toward more efficient and low-carbon production methods, resulting in a positive impact on the environment. In columns (2) and (5), the digital coefficients in the models with a low degree of patents and invention patents are significantly negative, suggesting that developing regions are more likely to be backward in terms of science and technology, in addition to the capacity to utilize digitalization for innovative development. Similar to the results of innovation, the digital coefficients are significantly positive in column (7). Upon rigorous analysis, it is evident that the coefficient of determination for the digital variable in the column highlights the pivotal role of the digital economy in enhancing the optimization and upgrade of industrial structure (8), which is statistically significant and exhibits a significant negative correlation, whereas that in column (9) is insignificant. The study's findings suggest that the impact of digitalization is most pronounced in regions with a less advanced industrial foundation. To reduce the pollutant emissions, industrial firms should accelerate their transition from low-level manufacturing to high-tech manufacturing by implementing technological innovations and upgrading equipment.

Table 7. The impact of the digital economy on the macro-mechanism of CO_2 emissions.

	(1) Total Patent	(2) Low-Level Patent	(3) High-Level Patent	(4) Total Invention Patent	(5) Low-Level Invention Patent	(6) High-Level Invention Patent	(7) Industrial Structure	(8) Low-Level Industrial Structure	(9) High-Level Industrial Structure
Digital	0.335 ***	−0.285 ***	−0.152	0.284 ***	−0.238 ***	−0.138	0.336 **	−0.203 *	−0.072
	(0.080)	(0.087)	(0.097)	(0.090)	(0.081)	(0.088)	(0.142)	(0.109)	(0.098)
N	1716	858	857	1716	857	858	1716	858	856
R-squared	0.835	0.749	0.737	0.799	0.717	0.755	0.472	0.739	0.781

Note: The regression results include province fixed effects and year fixed effects, and the standard errors are clustered by province, which are reported in parentheses. Significance levels are indicated as follows: * $p < 0.1$, ** $p < 0.05$, and *** $p < 0.01$. Moreover, the usual controls were incorporated in the analysis.

4.4. Placebo Test

In this segment, a placebo experiment was carried out to strengthen the observed impacts of the digital economy on the level of carbon dioxide emissions. To conduct a placebo test, we randomly substituted the digital variable of one province with data from other provinces, creating a "false" digital economy index. Subsequently, we proceeded to estimate Equation (1) utilizing the spurious digital economy variable and preserved the resultant estimations. We conducted a simulation by repeating the process 500 times, which produced a density plot of the estimation coefficients on the placebo digital variable, as depicted in Figure 3. The results of the analysis indicate that the estimated coefficients of the digital economy variable are distributed in a symmetrical manner around a mean of zero, conforming to a standard normal distribution. This outcome confirms that the significant impact of the digital economy on CO_2 emissions is not influenced by unobserved factors. The benchmark estimation results presented in Table 2 were found to deviate significantly from the range of coefficients estimated through our simulation exercise, which further strengthens our confidence in the authenticity and testability of our research findings.

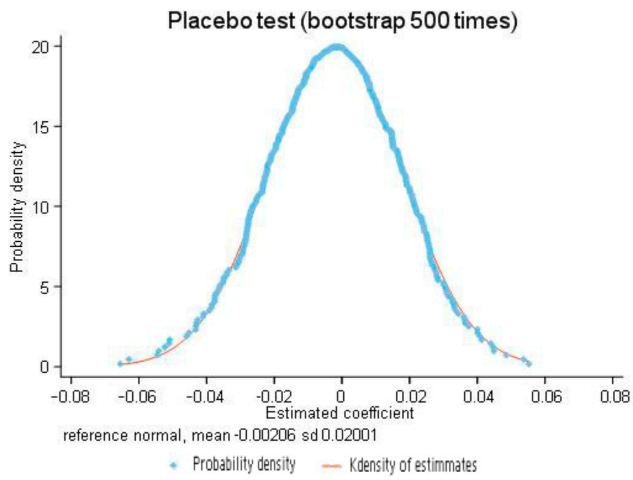

Figure 3. Placebo test (bootstrap: 500 times). Distribution of estimated coefficients.

5. Conclusions and Policy Recommendations

The aim of this paper was to investigate the potential role of the digital economy and environmental regulations in addressing the environmental consequences of CO_2 emissions. Considering digital technologies' immediate and intellectual characteristics, the digital economy could act as a positive contributor to tackling climate change and other environmental issues. To substantiate this argument, we first examined the correlation amid the digital economy and the environment. The results suggested that digitalization significantly decreases CO_2 emissions, and this negative relationship is more pronounced in affluent and densely populated regions. Next, we examined whether environmental regulations stimulate digitalization's productive role in carbon reduction. Our findings suggested that the digital economy has a significant impact on CO_2 emissions through environmental regulations, and the positive moderating effect of environmental department employees is more salient than environmental legislations and penalties. Lastly, we investigated other mechanisms via which the digital economy affects CO_2 emissions. We showed that digital technologies play a significant role in public participation in environmental protection, the technological innovation of firms, and real-time supervision of environmental violation activities. Overall, we showed that the digital economy is a crucial factor that significantly impacts CO_2 emissions by influencing the effectiveness of environmental regulations.

Addressing environmental issues and ensuring sustainable development are crucial topics for China and other developing nations. Hence, highlighting the potential benefits of digitalization and environmental regulations can offer valuable insights for addressing environmental pollution. Our research revealed a substantial negative correlation between the digitalization of the economy and the levels of carbon dioxide emissions, providing useful insights for decision makers across various societal domains. Moreover, we did not observe any significant impact of the digital economy on CO_2 emissions in less developed economies and sparsely populated regions, where the coefficient was still negative (as shown in Tables 3 and 5). Hence, policymakers in China should accelerate the construction of digitalization in less developed areas, comprehensively consider regional diversities, and adjust measures according to local circumstances.

In response to the findings of this paper, some relevant policy recommendations are provided. Firstly, using its legislative power and jurisdiction, the government should further strengthen law enforcement related to environmental protection and increase the penalties for environmental violations, thus effectively curbing environmental violations caused by enterprises in pursuit of profit. Secondly, the government should increase policy and financial support for technology-based and innovative enterprises, encourage and guide them to upgrade technologies related to energy conservation and environmental protection, use the information provided by digitization to drive technological innovation, and solve the pollution problems caused by enterprises in the production process from the source. In addition, policymakers should accelerate investment in digitization and the public should use internet and other online platforms to access environmental information and build awareness of their responsibility to protect the environment and save energy, thus enhancing the overall digitization of society and thus contributing to a favorable climate for environmental protection throughout society. Future research could further consider other impacts of digitization on the production areas of enterprises, such as energy efficiency and environmental information disclosure, to enrich research in related areas.

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