

The Impact of Digital Economy Development on Green Technology Innovation: Based on The Threshold Effect of Different Types of Environmental Regulations

Xinran Li^{1,a,*}

¹ College of Economic and Management, Harbin Normal University, Harbin, China

a. 3058849475@qq.com

*corresponding author

Abstract: Since entering the new norm, the digital economy has become an important driving force for China's economic transformation and upgrading. Based on the panel data of China's provinces from 2011 to 2021, the relationship between digital economy development, green technology innovation and environmental regulation is studied by using panel threshold model. The results show that the influence of the development of digital economy on green technology innovation is U-shaped. When the degree of formal environmental regulation crosses a single threshold, the incentive impact on innovation in green technologies is weakened, while the degree of informal environmental regulation crosses a triple threshold, the incentive impact on green technology innovation is gradually increased. The innovation effect of digital economy on green technology has regional heterogeneity. The east region and highly industrialized areas have a higher degree of economic development, which plays more significant role in promoting the level of green technology innovation. Therefore, we should make great efforts to develop the digital economy, promote the coordination of environmental regulation, strengthen regional cooperation as well.

Keywords: digital economy development, green technological innovation, environmental regulation

1. Introduction

On the critical period of transformation of Chinese economic growth mode from traditional factor-driven to green total factor productivity and technological innovation-driven [1], digital economy has become a major impetus to raise the level of green technological innovation. The 20th Party Congress's Report made it more clearly to speed up the development of the digital economy, to coordinate as well as advance the deep integration of digital economy with real economy [2]. Green technology innovation, as a primary impetus of green development, contributes to achieving the major strategic goal of Beautiful China' [3].

Digital economic development and green technological innovation are a unity of mutual influence. And environmental regulation, with its core of protecting ecological environment, reducing pollution emission and resource waste [4], greatly promotes the sustainable economy development as well as enhances the green technological innovation degree. Therefore, this paper intends to research the

impact relation between digital economic development, green technological innovation and environmental regulation.

2. Literature Review

2.1. Impact of Digital Economy Development on Green Technology Innovation

The “digital economy” refers to new economic model that promotes the optimization and upgrading of the economic structure. Bukht and Heeks considered that the “digital sector” at the heart of digital economy, i.e. IT/ICT industry that provides basic electronic products and services[5]. Wang et al. constructed an evaluation index system of digital economy[6], based on development environment, infrastructure, digital industrialization and digitization of industry. In the process of establishing a modern industrial system in China, the digital economy keeps an indispensable part, so accelerating the development of digital economy greatly facilitates the construction of the new development way as well as promote high quality development.

From the existing literature, most domestic scholars believe that digital economic development has a significant incentive effect to green technology innovation. Qiao, S. C. successively constructed Fixed Effect Model, Space Durbin Model[7], Intermediate Effect Model and Moderating Effect Model, and verified through empirical analyses that the digital economy development presents a manifest promotion influence to green technology innovation. Zhang, Y. W. found that digital economy development level presents facilitating effect and space spillover effect on green technology innovation, simultaneously, there is a regional difference, that is, in the eastern region, its influence is more manifest, while in both east and west regions, its influence is not manifest[8]. Ren and Yin based on China’s inter-provincial panel data, empirically examined the coordination of digital economy development and green technology innovation presents a significant incentive effect on Chinese carbon finance development[9]. Cheng et al. claim that green technological innovation is an indispensable way for digital economy to speed up high quality economic development, and this mediating effect still keeps after Sobel test[10].

2.2. Impact of Environmental Regulation on Green Technology Innovation

Environmental regulations refer the government regulations, guidance, restrictions on the economic activities of individuals and enterprises in order to protect the environment as well as achieve development sustainably, which will be specifically separated to formal and informal environmental regulations [11]. Formal environmental regulations are government's use of policies and laws, standards and norms, economic instruments and administrative supervision and other measures, through mandatory measures to control and reduce environmental pollutions; informal environmental regulations refer the public, civil society organizations and other non-government entities through social evaluation, self-regulatory behavior and other mechanisms for monitoring and restricting environmental behaviors, which do not have legal constraints but still keep a significant supervisory part.

In the literature similar to this paper’s topic, scholars from China and abroad have pointed out rich study around impact of environmental regulations on green technology innovations, which can be mainly divided into three typical views: First, the positive innovation compensation impact, under Porter’s hypothesis, Porter and Van proposed the innovation compensation influence, which believes that environmental regulations will hinder the profitability of enterprises in short terms, however, in long terms, they can stimulate enterprise to obtain long-term competitive advantage through innovative means, and make up for the increase in input costs of environmental innovation[12]. Secondly, for the negative “compliance cost effect”, Xiao et al. on the basic of two-way fixed model research found that China's implementation of environmental regulation on green technology

innovation showed significant inhibition of environmental regulation implementation, due to more stringent formal environmental regulations brought about by the higher emission standards, resulting in higher production costs, playing a negative “compliance cost” effect[13]. Kemp and Pontoglio argue that environmental regulations make firms bear higher emission costs, and therefore have a dampening effect on technological innovation. Thirdly, for the “innovation uncertainty effect”[14], Xu et al. believe that due to the deviations in types of environmental regulations, there also have deviations in effect of environmental regulations on green technology innovation.

The marginal contribution of this paper is mainly reflected in the following: from the perspective of different types of environmental regulations, the specific influence mechanism of digital economy development on green technology innovation is deeply analyzed, and analyses the different impacts on digital economic development on green technology innovation under constraints of different environmental regulations.

3. Theoretical Mechanism and Research Hypothesis

In early phase of digital economic development, the input costs of digital products and services may be greater than their revenues, which may have a negative influence on green technological innovations. At macro degree, digital economy may contribute to breaking spatial barriers which exist between green technology innovation [15], promoting regional integration and information share among innovational subject, laying favorable foundation on green technology innovation. good foundation. In light of this, this paper puts forward hypothesis 1.

H1: The impact of digital economy development on green technology innovation shows U-shaped characteristics.

According to the neoclassical growth theory [16], it is believed that official environment regulation restricts innovations space of companies, it will also make the production cost increase, its promotional influence on green technological innovation may be inhibited as well. In the digital era, the main channels for public participation and access to information are the Internet and social media platforms, when the strength of informal environment regulations are nonclear, its promotion on green technological innovations are limited. With the increasing intensity of informal environmental regulation, enterprises and residents have more extensive participation and more flexible feedback mechanisms. In light of this, this paper proposes hypothesis 2.

H2: Formal and informal environmental regulation have different threshold impact on digital economy to drive the growth of green technology innovation levels.

Digital economic development is a key driver of green technological innovation. Due to differences in geography and resources, regional disparities affect the influence of digital economy on innovation. The eastern region, with higher economic development, better infrastructure, and greater government support, fosters more green technological innovation. Additionally, high industrialization in these regions provides a strong economic base, skilled talent, and a reasonable industrial structure, supporting green technology innovation. This leads to hypothesis 3.

H3: There is regional heterogeneity in the innovative role of digital economic development for green technologies.

4. Model Construction and Empirical Analysis

4.1. Model Setting

So as to demonstrate the relation among digital economy development, environmental regulation, green technological innovations, this paper constructs following benchmark regression model.

$$gti_{it} = \alpha_0 + \alpha_1 de_{it} + \theta X_{it} + \mu_i + \omega_t + \varepsilon_{it} \quad (1)$$

In model (1), gti is green technology innovation, de represents digital economic development degree, X_{it} delegates a set of control variable, i delegates province, t represents year, α is the coefficient with estimation, μ_i represents province fixed effect, ω_t represents time fixed effect, and ε_{it} represents random error terms.

Since the transmission mechanism of digital economy is complex and further research on needed, square term of the digital economy is added based on model (1) as shown in (2)

$$gti_{it} = \alpha_0 + \alpha_1 de_{it} + \alpha_2 de_{it}^2 + \theta X_{it} + \mu_i + \omega_t + \varepsilon_{it} \quad (2)$$

For further discuss its influence mechanism on digital economy development level to green technology innovations under different types of environment regulations, environmental regulations are used to a threshold variable to build threshold effect model, as shown in equation (3).

$$gti_{it} = \alpha_0 + \alpha_1 de_{it} \times I(er_{it} \leq \gamma_1) + \alpha_2 de_{it} \times I(er_{it} > \gamma_1) + \theta X_{it} + \mu_i + \omega_t + \varepsilon_{it} \quad (3)$$

In view of the possibility of multi-threshold, single threshold panel regression model is expended to multi-threshold panel regression model, as shown in equation (4).

$$gti_{it} = \alpha_0 + \alpha_1 de_{it} \times I(er_{it} \leq \gamma_1) + \alpha_2 de_{it} \times I(\gamma_1 < er_{it} \leq \gamma_2) + \dots + \alpha_n de_{it} \times I(\gamma_{n-1} < er_{it} \leq \gamma_n) + \alpha_{n+1} de_{it} \times I(er_{it} > \gamma_n) + \theta X_{it} + \mu_i + \omega_t + \varepsilon_{it} \quad (4)$$

Where: er_{it} denotes environment regulation intensity of province i in year t (which may further subdivided to official environmental regulation fer_{it} and informal environment regulations ier_{it}), $I(-)$ represents the indicator function, whose value is dependent on relation between threshold variable and threshold value, if the equation in parentheses is valid, $I(-) = 1$, otherwise $I(-) = 0$, and γ denotes threshold value to be estimated.

4.2. Description of Variable

4.2.1. Explained Variable

Green technology innovation (gti) represents explanatory variable of here, referring to Previously scholars' research methods, this paper adopts green patent applications in each province as a measure of green technology innovations.

4.2.2. Core Explanatory Variable

This paper chooses digital economy (de) represents explanatory variable, refers to article of Zhao et al. measuring complex development degree of digital economy based from angle of Developing Network and Digital Financial Integration, selects Internet penetration rate, relevant practitioners, related outputs, mobile Internet users number, and development level of digital financial inclusion as second-level indexes, and uses principal component analysis to measure comprehensive development degree of digital economy The comprehensive development degree of digital economy will be measured using principal component analysis.

4.2.3. Threshold Variable

Environmental regulation represents threshold variable on this paper, which is further classified to official environment regulation (fer) as well as informal environment regulation (ier). Official environment regulation responds to degree of importance attached to environmental governance by government departments, and here refers study which accepts the percent of inter-provincial

investment in industry pollution control to GDP to measure; Informal environment regulation responds to the degree of importance attached to environmental governance by the general public, and here depend the method of Pargal et al., it adopts a series of indicators, for example, income degree, education level, population density, age construction, through the entropy value, measuring importance level of environment regulation.

4.2.4. Control Variable

Urbanization rate (ur), i.e. sharing the urban resident in the summary resident of the province; Fiscal decentralization (fd), obtained by calculating the inter-provincial budgetary every capital fiscal expenditure / (inter-provincial budgetary every capita fiscal expenditure + central budgetary every capita fiscal expenditure); Foreign direct investment (fdi), measured using a ratio from total FDI to regional GDP taken as natural logarithm.

4.2.5. Data Source and Descriptive Statistics

Here selects the panel data of China's 31 provinces (exclude Hong Kong, Macao and Taiwan) from 2011 to 2021, and these data are mainly obtained from China's Statistical Yearbook, China's Energy Statistical Yearbook, China's Environmental Statistical Yearbook, etc., and its descriptive statistics of every one is shown in Table 1.

Table 1: Descriptive statistics of variables.

Variable	Mean	Std. Dev.	Min	Max
gti	0.642	0.931	0.001	5.620
de	0.600	0.067	0.486	0.886
desq	0.364	0.084	0.236	0.785
fer	1.269	0.877	0.164	4.625
ier	0.222	0.120	0.087	0.881
ur	0.585	0.131	0.230	0.940
Ln(fd)	2.155	0.045	2.062	2.262
Ln(fdi)	-4.432	1.281	-10.641	-2.112

5. Analysis of Empirical Results

5.1. Benchmark Model Regression

For ensuring the robustness of study result, here accepts the stepwise methodology of appending variable to the benchmark regressions, as well as relevant results have as shown to Table 2. Among them, column (1) is a univariate regression of digital economy to green technological innovations; column (2) adds squared term of control variable digital economy; column (3) further adds the control variable urbanization rate; column (4) continues to add fiscal decentralization as a control variable; and column (5) finally adds foreign direct investment as a control variable, thus forming the final benchmark regressions model.

Table 2: Benchmark regression results.

Variable	(1)	(2)	(3)	(4)	(5)
de	10.095* (5.345)	-41.778* (23.135)	-39.526* (20.978)	-40.972* (20.567)	-40.921** (19.125)

Table 2: (continued).

desq	32.696** (13.690)	30.873** (12.840)	31.066** (12.775)	28.883** (11.837)
ur		-0.922 (2.869)	-2.393 (2.972)	-2.917 (2.984)
Ln(fd)			13.877** (5.659)	8.128** (3.588)
Ln(fdi)				0.239* (0.138)
Time fixed				
Province fixed		Yes		
Constant term	-5.066* (2.773)	13.032 (8.432)	12.837 (0.119)	-15.531* (8.279)
N			341	
R ²	0.414	0.491	0.492	0.530
			0.530	0.569

Note: ***, **, and * are significant at 1%, 5%, and 10% respectively, and are robust standard errors in parentheses. No further details will be done, and only core variables will be discussed, the same below.

The results of benchmark regressions are shown in Table 2, with column (1) is regression result for only core explanatory variable of digital economy, whose regression coefficient is greatly incentive on 10 percent degree. In the model further introduction of variables desq again regressions, the result is shown in column (2), its result show there has U shaped relations in digital economy and green technology innovation. Columns (3) to (5) in Table 2 show the goodness of fit of model increases by continuous addition of each control variable, and the coefficient of the digital economy has remained significant in this process.

5.2. Robustness and Endogeneity Tests

Samples from Beijing, Tianjin, Shanghai, and Chongqing are excluded before regression. A 1% shrinkage treatment is applied to eliminate extreme observations, improving model reliability. Then, using Feng and Xu's method, a lagged explanatory variable is regressed for an endogeneity test, confirming the significance of the findings without substantial changes.

Table 3: Robustness and endogeneity tests.

Variable	Excluding	shrinkage	Variable lagged
de	-71.253*** (25.047)	-49.994*** (17.114)	-41.545** (18.681)
Constant term	5.067 (10.687)	0.873 (7.598)	-2.035 (10.595)
Time fixed		Yes	
Province fixed			
R ²	0.542	0.594	0.566
N	297	341	310

5.3. Threshold Effect Test

Its relation between development degree of digital economy and green technology innovation isn't just linear relation lonely, but there may also be significant non-linear threshold effects. As

environment control intensity increases, its impact about digital economy on green technological innovations may have a jump change rather than a linear change. Therefore, in order to further explore the non-linear influence about digital economy on green technological innovations, here utilize a panel threshold model regression to testify whether different types about environmental regulation constrain this impact.

First, panel threshold existence test has constructed, while the number of thresholds is determined and repeated self-sampling is performed 300 times by Bootstrap to attain F-statistic as well as p-value, respectively. Test result have shown in Table 4.

Table 4: Threshold effect test results.

Threshold variable	N	F-statistic	P-value	threshold value
fer	single	19.97	0.070	0.443
ier	single	38.15	0.027	0.248
	double	199.86	0.000	0.273
	triple	43.52	0.007	0.286

When formal environmental control intensity is below 0.443, the digital economy significantly boosts green technological innovation, with a coefficient of 9.122. Above this threshold, its influence weakens to 8.475. With low environmental regulation, businesses have more freedom to innovate, while stricter regulations focus their innovations on government policies, reducing the digital economy's impact. For informal regulations, when intensity is below 0.248, the relationship remains positive (6.019), increasing with higher regulation intensity. Beyond 0.286, the digital economy's influence grows stronger. Low informal regulation limits public participation and resource-sharing, weakening its impact on innovation. This supports hypothesis 2.

Table 5: Threshold regression results of digital economy affecting green technology innovation.

Variable	fer	ier
$de \times I(fer \leq \gamma_1)$	9.122*** (0.870)	
$de \times I(fer > \gamma_1)$	8.475*** (0.907)	
$de \times I(ier \leq \gamma_2)$		6.019*** (0.651)
$de \times I(\gamma_2 < ier \leq \gamma_3)$		6.446*** (0.654)
$de \times I(\gamma_3 < ier \leq \gamma_4)$		7.400*** (0.639)
$de \times I(fer > \gamma_4)$		9.045*** (0.620)
constant	-18.181*** (6.411)	-10.641** (4.611)
$\gamma_1(\gamma_2, \gamma_3, \gamma_4)$	0.443	0.248, 0.273, 0.286
N		341
R^2	0.506	0.747

5.4. Heterogeneity Analysis

5.4.1. Regional Heterogeneity

Due to varying regional developments, the impact of digital economy on green technological innovations differs across regions. Based on regional classifications, this study divides China into east, central, and west. The regression results show that digital economy significantly promotes green

innovation, with the eastern region having the strongest impact, followed by central and western regions.

Table 6: Analysis of regional heterogeneity.

Variable	Eastern	Central	Western
de	12.475*** (1.257)	3.897*** (1.165)	2.457*** (0.446)
Constant term	17.463 (11.449)	4.184 (3.556)	4.104** (1.604)
Time fixed		Yes	
Province fixed			
R^2	0.646	0.743	0.548
N	121	99	121

5.4.2. Heterogeneity in the Degree of Industrialization

To test if digital economy's influence on green technology innovation differs by industrialization, provinces were classified based on the second industry's contribution to GDP. Regions with above-average second industry value were classified as high-industrialized. Regression results show that digital economy has a stronger impact on green innovation in high-industrialized regions, with a 1% increase in the digital economy leading to a 24.455% rise in green innovation. In low-industrialized regions, the increase is only 12.142%. This supports hypothesis 4.

Table 7: Heterogeneity analysis of degree of industrialization.

Variable	High	Low
de	24.455** (20.239)	12.142*** (3.053)
Time fixed		Yes
Province fixed	0.617	0.716
N	180	161

6. Conclusion and Recommendation

6.1. Conclusion

Based on data of China's provinces from 2011 to 2021, here draws subsequent conclusions:

First, the influence about digital economic development on green technological innovations present U-shaped characteristics. Second, on facilitating green technology innovation stage in the digital economy, official and informal environment regulation play diverse roles. Thirdly, the digital economy development and green technological innovation is uneven among regions in China.

6.2. Recommendation

In view of empirical results above, subsequent policy recommendations have made:

First, it should focus on cultivating digital talents, improving the level of digitalization in China, and establishing a digital information-sharing platform to provide a constant flow of information resources in order to develop green technological innovations.

Secondly, to promote coordinated development about official as well as informal environment control, simultaneously, to encourage green technological innovations based on environmental regulation.

Thirdly, regional synergies need be actively exploited and regional cooperation need be consolidated. Government should maintain development advantages of the eastern region, while giving corresponding preferential policies and resource support to central and west region.

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