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Digital Economy, Technological Innovation, and Environmental Pollution in Different Regions: An Analysis Based on a Threshold Model

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Abstract. The digital economy significantly promotes fundamental innovation activities and impacts environmental pollution through mechanisms such as optimizing resource allocation, accelerating knowledge flow, and enhancing innovation service efficiency. Based on panel data from 29 provinces in China from 2010 to 2020, this paper employs a panel threshold regression model to investigate the relationship between the digital economy, fundamental innovation, and environmental pollution. The study finds a significant negative correlation between the level of digital economy development and environmental pollution. As the digital economy level increases, the environmental pollution levels in the relevant provinces significantly decrease. Additionally, the impact of technological innovation on the relationship between the digital economy and environmental pollution exhibits nonlinear characteristics. When the level of technological innovation exceeds a specific threshold, the effect of the digital economy on reducing environmental pollution is significantly enhanced. There are regional differences in how digital economy development and technological innovation levels affect environmental pollution. In the eastern coastal regions, where the digital economy and technological innovation are more advanced, the reduction effect on environmental pollution is more pronounced, whereas the effect is relatively limited in the central and western regions. This study provides theoretical support and decision-making references for the construction of ecological civilization and green, low-carbon development.

Keywords: digital economy, fundamental innovation, environmental pollution, panel threshold regression model, regional differences

1. Introduction

Digital transformation and green low-carbon transition are two major transformative trends shaping the future globally. China places significant emphasis on the development of the digital economy, elevating it to the level of a national strategy. In 2020, the added value of core industries in China's digital economy accounted for 7.8% of the Gross Domestic Product (GDP). This proportion is expected to increase to 10% by 2025. [10] Simultaneously, the global trend towards green low-carbon transition is accelerating, with countries worldwide engaging in a new wave of industrial and technological revolutions characterized by green and low-carbon principles, thereby promoting the development of the global green economy.

Under the guidance of the "dual carbon" goals, China is actively promoting comprehensive, high-quality socio-economic development. Digitalization and low-carbonization, as interdependent and mutually reinforcing entities, jointly propel the green development of human society. Digital empowerment is a crucial pathway for green low-carbon transition, while green transition requires robust digital technology support. Accelerating the construction of a Digital China is not only of great significance for the comprehensive building of a modern socialist country but also has profound implications for the advancement of the great rejuvenation of the Chinese nation.

Therefore, exploring the relationships among the digital economy, fundamental innovation, and environmental pollution, and constructing a comprehensive analytical framework that encompasses these elements, will help to comprehensively understand the new characteristics of environmental pollution control in the digital economy era. Investigating the nonlinear regulatory role of technological innovation levels and regional differences will further enhance this understanding.

2. Literature Review

2.1. Digital Economy and Technological Innovation

The rapid development of the digital economy has profoundly altered the innovation models and ecosystems of enterprises. Zhang pointed out that digital technologies promote technological innovation in enterprises by changing resource allocation methods and innovation organizational structures. [23] Afonasova et al. emphasized that digital technologies play a crucial role in promoting innovation, not only improving production efficiency but also fostering the development of new products and services. [1] Ruslan and Tatjana discussed the role of digital technologies in enhancing the innovation capabilities of enterprises, highlighting that the digital economy, through data sharing and information exchange, enhances collaborative innovation among companies. [13] Additionally, Yu and Li noted that the digital economy, through emerging formats such as internet platforms and e-commerce, provides more innovation opportunities and market space. [21] Thus, the digital economy significantly drives the development of technological innovation through the widespread application of digital technologies.

2.2. Digital Economy and Environmental Pollution

The impact of the digital economy on environmental pollution is multifaceted. Deng and Zhang found that the digital economy significantly reduces urban pollutant emissions, with the most notable effect on reducing industrial sulfur dioxide emissions, indicating the important application prospects of digital technologies in industrial pollution control. [4] Shahbaz et al. explored the role of the digital economy in promoting renewable energy consumption and production globally, pointing out that digital technologies can optimize energy use efficiency and reduce reliance on traditional fossil fuels, thereby lowering pollution emissions. [14] Miao et al. noted that the digital economy has an inverted U-shaped impact on carbon emissions and indirectly reduces carbon emissions by improving innovation efficiency. [12] Feroz et al. similarly highlighted the significant impact of digital transformation on pollution control, waste management, sustainable production, and urban sustainable development, emphasizing that digital technologies play a crucial role in promoting environmental sustainability. [6] In summary, the development of the digital economy contributes to reducing environmental pollution to a certain extent, particularly in enhancing green technological innovation and energy transition.

2.3. Technological Innovation and Environmental Pollution

Technological innovation plays a crucial role in environmental pollution control. Yuan and Xie pointed out that there is an inverted U-shaped relationship between industrial agglomeration and environmental pollution, where technological innovation plays a key role in determining the position of the “inflection point.” [20] This relationship indicates that in the initial stages of industrial agglomeration, the concentrated use of resources may lead to increased environmental pollution. However, with the introduction and application of technological innovation, the negative impact of industrial agglomeration on the environment gradually diminishes and may even transform into a positive effect. Fan and Sun (2020) explored the impact of environmental regulations on green technological innovation and the green economy, noting that market-incentive-based environmental regulations significantly promote green technological innovation when they exceed a certain threshold, whereas command-and-control regulations have a less pronounced effect. [5] This suggests that market mechanisms have greater potential in driving enterprises towards green technological innovation. Fischer et al. analyzed the impact of environmental regulations on technological innovation and pollution control, highlighting that stringent environmental regulations can prompt enterprises to reduce pollutant emissions while simultaneously improving production efficiency, achieving a win-win situation for both the economy and the environment. [7] Furthermore, technological innovation is not limited to improvements in pollution control technologies but also encompasses the development and application of clean production technologies and circular economy technologies, which play a significant role in reducing pollutant emissions and improving resource utilization efficiency. [15]

Existing literature has not yet clarified the internal mechanisms through which the digital economy influences environmental pollution by affecting fundamental innovation. Therefore, this paper constructs a comprehensive analytical framework that includes the digital economy, fundamental innovation, and environmental pollution. Using a panel threshold effect model, we examine the pathways and characteristics of how the digital economy affects environmental pollution through fundamental innovation. On the one hand, we delve into the relationship between the level of digital economy development and environmental pollution. On the other hand, we analyze the nonlinear moderating effect of technological innovation levels on the relationship between the digital economy and environmental pollution, exploring how digital economy growth impacts environmental pollution when technological innovation levels exceed a specific threshold. Additionally, this paper will investigate the regional differences in the impact of digital economy development and technological innovation levels on environmental pollution.

3. Theoretical Analysis and Research Hypotheses

The digital economy can be divided into two main components: digital industrialization and industrial digitalization. The rise of this field is considered a key force in promoting sustainable development. The digital economy not only transforms business models and industrial structures but also provides innovative solutions for environmental protection [8]. By leveraging advanced data processing capabilities and intelligent technologies, the digital economy helps enhance resource utilization efficiency, reduce resource waste, and promote the development and application of environmental technologies [4]. Moreover, with the aid of intelligent management systems and Internet of Things (IoT) technologies, it has become possible to effectively monitor and reduce pollutant emissions. Based on this, the first hypothesis is proposed.

H1: There is a significant negative correlation between the level of digital economy development and environmental pollution. As the level of the digital economy increases, the environmental pollution levels in the relevant provinces will be effectively reduced.

In modern economies, technological innovation is regarded as the main driving force behind sustainable development. Particularly in the realm of the digital economy, technological innovation not only facilitates the emergence of new technologies and business models but also has the potential to reduce environmental pollution through intelligent solutions [15]. However, technological innovation requires a series of accumulations and applications to reach a certain maturity before it can play a crucial role in environmental protection. In the initial stages of development in various provinces of China, the impact of the digital economy on reducing environmental pollution may be limited, as the digital economy needs time to surpass a certain threshold [22]. Therefore, the nonlinear nature of technological innovation means that its positive effects on the environment may significantly increase after reaching a critical point, forming a notable threshold effect. Based on the above observations, the second hypothesis is proposed.

H2: The level of technological innovation exhibits a nonlinear moderating effect on the relationship between the digital economy and environmental pollution. When the level of technological innovation exceeds a specific threshold, the effect of digital economy growth on reducing environmental pollution is enhanced.

Due to differences in resource endowments and infrastructure construction levels, the development of the digital economy in different regions of China is also uneven. Regions with well-developed infrastructure tend to attract more technological investments, thereby accelerating the development of the digital economy [18]. However, according to the hypothesis of the resource curse, in regions rich in natural resources but relatively underdeveloped in infrastructure, economic development often overly relies on resource extraction, hindering the formation of a diversified economic structure, including the digital economy [17]. Thus, the imbalances in economic development levels, the degree of technology application, policy support, and geographical environment, along with differences in resource endowments and infrastructure, collectively shape the regional heterogeneity in the impact of technological innovation and the digital economy on environmental pollution [3]. Based on this, this paper further explores the impact of regional differences on the hypotheses and proposes the third hypothesis.

H3: There are regional differences in the impact of digital economy development and technological innovation levels on environmental pollution. Specifically, the eastern coastal regions, where digital economy development and technological innovation are faster, exhibit more significant effects on reducing environmental pollution, whereas the role of the digital economy in environmental improvement is limited in the central and western regions.

4. Variable Explanation and Model Establishment

4.1. Data Sources and Descriptive Statistics

This study utilizes data from 29 provinces in China for the period from 2010 to 2020, excluding Tibet, Xinjiang, Hong Kong, Macau, and Taiwan. The data are sourced from the China Environmental Statistics Yearbook, China Statistical Yearbook, China Information Industry Yearbook, and various provincial statistical yearbooks. Missing values are supplemented using linear interpolation.

Descriptive statistics reveal that in the early stages, the western regions of China, due to geographical disadvantages and limitations in economic development levels, received relatively less investment, directly affecting the overall development level of the digital economy in these areas. However, with the implementation of a series of digital economy innovation and development policies targeted at the western regions, the level of the digital economy in these areas has significantly improved. Additionally, the study finds that there is also an uneven distribution of technological innovation capabilities across regions. Coastal provinces generally have higher investments and achievements in technological innovation compared to inland regions, further highlighting the imbalance in regional development within China.

Table 1. Descriptive Statistics of Variables

Variable	Mean	St.Err.	Min	Max
InDEI	0.596	0.066	0.486	0.886
urban	0.593	0.123	0.350	0.896
InTIAV	9.081	0.920	6.499	11.044
InSO2	3.219	1.266	-1.735	5.209
InConsumer	17.824	2.342	-0.440	19.878

Table 1. Continued

InTec	7.618	1.913	0.000	12.511

4.2. Variable Selection

Dependent Variable: Current research tends to select a specific pollutant as a representative indicator for evaluating the environmental quality of a region. Among various pollutants, sulfur dioxide (SO_2) monitoring data in China is more reliable and complete compared to other pollutants. Therefore, this study chooses industrial SO_2 emissions to measure the degree of environmental pollution [16].

Core Independent Variable: To measure the digital economy level of each province, this paper introduces the Digital Economy Index (DEI) as the core independent variable. Drawing on Liu's research, this paper divides the digital economy level into two primary indicators: digital industrialization and industrial digitalization, to comprehensively assess the development level of the digital economy. [11] Digital industrialization focuses on industries directly involved in the research and application of digital technologies, while industrial digitalization focuses on the transformation and upgrading of traditional industries through the application of digital technologies.

Threshold Variable: This paper selects patent output as the indicator to measure the level of technological innovation. This choice is primarily because patents directly reflect the commercialization and practical application potential of innovation outcomes. Compared to R&D investment, patent data is more straightforward and standardized, making cross-provincial comparative analysis more feasible. Additionally, using the logarithmic form has the advantage of mitigating the impact of extreme values, enhancing the stability of statistical analysis, and facilitating the assessment of relative changes in patent numbers across different regions [15].

Control Variables: To more precisely analyze the impact of the digital economy level on environmental pollution, this paper selects the urbanization rate (urban), tertiary industry added value (TIAV), and the total retail sales of consumer goods (consumer) as control variables [10, 19].

4.3. Empirical Model

To examine the relationship between environmental pollution levels, digital economy development levels, and technological innovation, this paper constructs the regression model as shown in Equation (1).

$$ln\,Y_{it} = \alpha_0 + \alpha_1\, ln\, DEI_{it} + \alpha 2\, ln\, Tec_{it} + \theta X_{it} + \varepsilon_{it} \quad (1)$$

In Model (1), Y represents the level of environmental pollution, DEI is the composite index of the digital economy level, and X denotes a series of control variables. The subscript i indicates the province, t indicates the year, α represents the coefficients to be estimated, and ϵ represents the random error term.

To further discuss the impact mechanism of digital economy development levels under different technological innovation levels, this paper constructs a threshold effect model with technological innovation level as the threshold variable, as shown in Equation (2).

$$ln\,Y_{it} = \alpha_0 + \alpha_1\, ln\, DEI_{it} \times I(ln\, Tec_{it} \le \gamma_1) + \alpha_2\, ln\, DEI_{it} \times I(\gamma_1 < ln\, Tec_{it} \le \gamma_2) + \alpha_3\, ln\, DEI_{it} \times I(ln\, Tec_{it} > \gamma_2) + \theta X_{it} + \varepsilon_{it} \quad (2)$$

In Equation (2), $I(\cdot)$ is an indicator function that takes the value of 1 if the condition within the parentheses is true and 0 otherwise.

5. Empirical Results Analysis

5.1. Baseline Regression Analysis

To assess the impact of digital economy development levels on environmental pollution, this study employs panel data and first applies the Hausman test to select the appropriate model based on the data characteristics. In this study, the results of the Hausman test show a p-value of less than 0.001, supporting the use of the fixed effects model.

The baseline regression results of the impact of digital economy development levels on environmental pollution are shown in Table 2. Columns (1) to (4) in Table 2 present the regression results with control variables added step by step. The results indicate that the improvement in the digital economy development level significantly reduces the level of environmental pollution, confirming that the digital economy development level has a negative promoting effect on environmental pollution. Specifically, if the digital economy development level in a province increases by one unit, the SO_2 emissions in that province decrease by 13.455 units, thereby validating Hypothesis 1.

The model analysis that introduces the urbanization rate as a control variable shows that the increase in urbanization rate is generally accompanied by an increase in environmental pollution. This phenomenon can be attributed to the intensified industrialization and increased population density during the urbanization process, leading to excessive resource consumption and rising waste emissions.

Moreover, when the tertiary industry added value is included in the model, the results show that the growth of the tertiary industry is positively correlated with the reduction in environmental pollution. However, after introducing the tertiary industry added value, the mitigating effect of the digital economy on environmental pollution is somewhat weakened. In regions where the tertiary industry is more developed, the direct contribution of the digital economy to environmental improvement may be partially offset by the inherent environmental protection effect of the tertiary industry itself.

Table 2. Baseline Regression Results on the Impact of Digital Economy Index on Environmental Pollution Levels

	In Y			
	(1)	(2)	(3)	(4)
InDEI	-14.877 *** (0.762)	-17.482 *** (1.643)	-13.504 *** (1.301)	-13.455 *** (1.307)
urban		3.636 * (1.987)	7.864 *** (2.825)	7.877 *** (2.842)
InTIAV			-1.142 ** (0.420)	-1.142 ** (0.420)
InConsumer				-0.009 *** (0.003)
Constant	12.082 *** (0.454)	11.477 *** (0.438)	16.974 *** (2.117)	17.088 *** (2.118)
R^2	0.804	0.810	0.819	0.819
N	290	290	290	290

Note: The numbers in parentheses represent robust standard errors. The symbols "***", "**", *and* "*" denote significance levels of 1%, 5%, and 10%, respectively. This rule also applies to the table below.

5.2. Panel Threshold Effect Analysis

This paper first tests the threshold effect of panel data. The experimental results initially confirm Hypothesis 2, indicating that the level of technological innovation exhibits a nonlinear moderating effect on the relationship between the digital economy and environmental pollution. Specifically, the panel data threshold effect test results show that the technological innovation level is significant in the single threshold test but fails to reach significance in the double and triple threshold tests.

According to the analysis results in Table 4 and Table 3, when the technological innovation level is below the threshold value of 9.624, the negative impact of digital economy development on environmental pollution is relatively small. However, once the technological innovation level exceeds this threshold value, the impact of the digital economy on the environment increases from -11.627 units to -12.406 units. This result indicates that after the technological innovation level reaches a certain threshold, the negative marginal effect of digital economy development on environmental pollution significantly intensifies, demonstrating a nonlinear diminishing characteristic.

This could be because a high level of technological innovation can more effectively promote the application of green technologies and improve resource utilization efficiency, thereby more significantly reducing environmental pollution.

Table 3. Test of Threshold Effects of Technological Innovation on Environmental Pollution Levels

Model	Threshold	MSE	F-stat	Prob	Crit10	Crit5	Crit1
Single	9.624	0.116	28.640	0.044	22.233	27.255	39.514
Double	8.032	0.114	4.990	0.756	13.699	16.843	24.795
Triple	9.058	0.112	4.960	0.670	11.649	13.866	17.611

Table 4. Regression Results of the Threshold Model on the Impact of Technological Innovation on Environmental Pollution

Threshold	$I(\ln Tec_{it} \leq \gamma_l)$	$I(\ln Tec_{it} > \gamma_l)$	Obs per Group	Number of Groups
9.624	-11.627***(1.738)	-12.406***(1.559)	10	29

6. Heterogeneity Analysis

Given the different stages of development across various regions, this study conducts a heterogeneity analysis of the provinces in China. Based on the statistical system and classification standards published by the National Bureau of Statistics, the provinces and cities are divided into four regions: the Eastern region includes 10 provinces (cities): Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan; the Central region includes six provinces: Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan; the Western region includes 10 provinces (autonomous regions, municipalities): Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, and Ningxia; and the Northeastern region includes three provinces: Liaoning, Jilin, and Heilongjiang.

The empirical analysis of the relationship between the digital economy development level and environmental pollution in each region is shown in Table 5. The results indicate that the digital economy development level in the Eastern region significantly reduces environmental pollution. The higher technological innovation capability and more complete infrastructure in the Eastern region jointly promote the positive effect of the digital economy on the environment. However, this effect is not significant in the Central and Western regions, possibly due to relatively lagging technological innovation and infrastructure construction in these areas.

Furthermore, the single threshold model for each region, as shown in Tables 6 and 7, indicates that only in the Eastern region does the impact of the digital economy on environmental pollution have statistical significance. The high threshold value in the Eastern region suggests that only when the digital economy development level surpasses this high threshold does it have a significant positive impact on the environment. In contrast, the threshold values in the other regions are relatively low, especially in the Northeastern region. This finding further reveals the leading position of the Eastern region in terms of the digital economy and environmental protection. The Eastern region needs to invest more resources and conduct more in-depth technological innovation in the digital economy to significantly improve environmental quality.

In the Central, Western, and Northeastern regions, despite lower threshold values, the positive effect of the digital economy on the environment is still difficult to manifest due to limitations in infrastructure and technological levels. Additionally, the regression results for the Northeastern region show a positive correlation between the digital economy development level and environmental pollution. The Northeastern region, dominated by traditional heavy industries, lags in digital economy development, leading to environmental pollution control relying on traditional high-pollution industries. Furthermore, the digital economy development in the Northeastern region has not yet effectively replaced traditional industries, which may explain why the digital economy's impact on environmental improvement has not been evident.

Analyzing the proportion of urbanization as a control variable reveals that, except for the Eastern region, the urbanization ratio in other regions is negatively correlated with environmental pollution. This may be because, in these regions, the increase in environmental protection infrastructure and technological investment during the urbanization process improves the efficiency of waste treatment and pollution control. In the Eastern region, however, the concentration of population density and industrial activities leads to increased resource consumption and pollution emissions. Rapid urban expansion often exceeds the carrying capacity of infrastructure, resulting in insufficient treatment of sewage, exhaust gases, and solid waste, thereby exacerbating environmental pollution problems.

The added value of the tertiary industry shows a negative relationship with environmental pollution in some developed regions, mainly because these regions' tertiary industries are dominated by high value-added and low-pollution sectors such as finance and information technology. In contrast, the tertiary industries in other regions are still developing, smaller in scale, and include sectors that significantly impact the environment, such as tourism and catering, thus the impact on environmental pollution is not significant.

Table 5. Heterogeneity Analysis of the Impact of Digital Economy Index on Environmental Pollution Across Different Regions

	In Y			
	Eastern Region	Central Region	Western Region	Northeastern Region
InDEI	-11.588 ***	-6.020	-2.109	10.737 **
	(2.461)	(5.412)	(2.247)	(1.612)
urban	10.610 **	-17.346	-11.523 **	-35.712 ***
	(4.338)	(11.618)	(4.951)	(1.452)
InTIAV	-2.684 **	-0.139	-0.488	-0.110
	(0.842)	(1.503)	(0.839)	(0.432)
InConsumer	1.068	1.235 *	0.541 *	-0.023 ***
	(0.642)	(0.542)	(0.271)	(0.001)
Constant	8.721	-5.213	5.321	20.694 **
	(8.342)	(6.971)	(5.024)	(2.122)
R^2	0.845	0.848	0.849	0.892

Table 5. Continued

N	100	60	100	30

Table 6. Single Threshold Effect and Regional Heterogeneity of Technological Innovation on Environmental Pollution

Region	Threshold	MSE	F-stat	Prob	Crit10	Crit5	Crit1
Eastern Region	9.624	0.127	34.380	0.004	19.838	22.976	27.160
Central Region	8.506	0.095	8.580	0.532	22.510	27.086	40.177
Western Region	8.212	0.076	5.770	0.348	9.190	10.958	14.591
Northeastern Region	6.827	0.054	4.100	0.486	8.333	10.425	10.425

Table 7. Regression Results of the Threshold Model on the Impact of Technological Innovation on Environmental Pollution – The Eastern Region

Threshold	$I(\ln Tec_{it} \le \gamma_I)$	$I(\ln Tec_{it} > \gamma_I)$	Obs per Group	Number of Groups
9.624	-8.060(4.057)	-9.143^{*}(3.780)	10	10

7. Robustness Test

To verify the reliability of the above conclusions, this study replaces the dependent variable. Specifically, the study uses the amount of solid waste generated to replace sulfur dioxide emissions as a measure of environmental pollution (Ji et al., 2015).

The regression results in Table 8 show that for each unit increase in the level of digital economy development, the amount of solid waste pollution decreases by 1.9 units, indicating a negative impact of digital economy development on solid waste generation. The threshold regression results in Tables 9 and 10 indicate that, in the single threshold model, once the technological innovation level reaches a specific threshold, the negative marginal effect of digital economy development on environmental pollution significantly intensifies, demonstrating a nonlinear diminishing characteristic. The results of both the baseline regression and the threshold regression models are consistent with the previous findings, confirming the reliability of this study.

Table 8. Robustness Check of the Baseline Regression Results on the Impact of Digital Economy Development on Environmental Pollution

	InDEI	urban	InTIAV	InConsumer	Constant	R^2	N
In Y	-1.938^{**} (0.909)	0.620 (2.578)	0.566 (0.351)	-0.019^{***} (0.003)	-2.815^{*} (1.524)	0.165	290

Table 9. Threshold Effect Test of Technological Innovation on Environmental Pollution

Model	Threshold	MSE	F-stat	Prob	Crit10	Crit5	Crit1
Single	7.306	0.061	38.600	0.050	31.461	37.937	46.121
Double	5.649	0.058	14.790	0.346	24.579	30.076	43.043
Triple	8.021	0.056	8.410	0.680	21.106	26.415	34.165

Table 10. Threshold Effect Test Results of Technological Innovation on Environmental Pollution

Threshold	$I(\ln Tec_{it} \le \gamma_I)$	$I(\ln Tec_{it} > \gamma_I)$	Obs per Group	Number of Groups
7.306	-2.432^{**}(1.017)	-3.138^{**}(1.199)	10	29

8. Conclusion and Policy Recommendations

8.1. Research Conclusions

Based on panel data from 29 provinces in China from 2010 to 2020, this paper employs a panel threshold regression model to investigate the relationships among the digital economy, basic innovation, and environmental pollution. The study yields the following conclusions: firstly, the improvement in the level of digital economy development significantly reduces the level of environmental pollution. Secondly, the level of technological innovation exerts a nonlinear moderating effect on the relationship between the digital economy and environmental pollution. When the level of technological innovation is below the threshold value, the impact of digital economy development on environmental pollution is relatively small. However, once the level of technological innovation surpasses this threshold, the negative marginal effect becomes significantly stronger. Lastly, there exist regional differences in the impact of digital economy development and technological innovation on environmental pollution. In the more economically developed eastern regions, the effects of the digital economy and technological innovation in reducing environmental pollution are more pronounced. In contrast, in the central, western, and northeastern regions, where technological innovation and infrastructure construction are relatively underdeveloped, and where there are unique characteristics in regional economic structures and industrial layouts, the impact of the digital economy on environmental governance is limited.

8.2. Policy Recommendations

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

First, regions should actively take measures to enhance the level of the digital economy. Primarily, the government needs to vigorously promote the digital transformation of enterprises. By providing financial support and technical guidance, the government can help enterprises introduce advanced digital technologies, thereby improving production efficiency and environmental standards. Simultaneously, the government should accelerate the construction of new infrastructure such as 5G networks, artificial intelligence, and big data centers. Furthermore, it should collaborate with universities and research institutions to cultivate talents with digital economy skills, providing professional technical support to enterprises.

Second, for regions with relatively low levels of technological innovation, it is crucial not to rely solely on the development of the digital economy to suppress environmental pollution; technological innovation is essential. The government should increase investment in scientific research and development, enhance financial support for research projects, and encourage enterprises and research institutions to carry out green technology innovation. At the same time, improving the intellectual property protection mechanism and strengthening the implementation of intellectual property laws and regulations are necessary to protect the rights of innovators.

Third, to narrow the gaps between regions, it is recommended that the central, western, and northeastern regions formulate preferential policies to attract talent and enterprises from the eastern regions to invest locally. Policies to attract talent, such as providing housing subsidies, children's education, and healthcare benefits, should be implemented to draw high-end talent to work in these areas. Additionally, enhancing cooperation between the eastern regions and the central, western, and northeastern regions is crucial. Accelerating the infrastructure construction in the central, western, and northeastern regions, promoting cross-regional industrial chain collaborative development, and sharing regional technologies and resources are all essential steps.

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