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Research on the Impact of Digital Economy on Green Technology Innovation of Chinese Enterprises

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Abstract: *This paper examines the correlation between digital economy development and green technology innovation, aiming to clarify the influence of digital economy development on green technology innovation. Based on the data of China's digital economy development and enterprise green technology innovation from 2012 to 2022, a fixed effect model is established to assess the influence of digital economy development level on enterprise green technology innovation. The findings indicate that the level of the digital economy exerts a significant positive impact on enterprise green technology innovation, with macro-level digital economy development enhancing micro-level enterprise green technology innovation. Additionally, R&D investment serves as a positive mediating factor in the relationship between the digital economy and enterprise green innovation. Compared with the western region, the digital economy in the eastern region exerts the most significant influence on green technology innovation. Consequently, the subsequent recommendations are proposed to enhance the development of digital economic infrastructure and refine the allocation of R&D expenditure.*

Keywords: *Digital economy; Green technology innovation; R&D investment*

1. Introduction and brief literature review

Since the reform and opening up, China's economy has undergone great progress and transformation, emerging as the world's second-largest economy. However, the process of economic expansion faces a series of problems, such as unbalanced regional development, inefficiency, energy waste, and inadequate scientific and technological innovation capacity, resulting in increased environmental costs[1]. In 2020, General Secretary announced the objective of reaching carbon peak by 2030 and attaining carbon neutrality by 2060. Under the huge pressure of internal and external environment, China's economic development is necessitating an urgent transition from a "quantitative" growth paradigm to a "qualitative" improvement. In recent years, the organic integration of the digital economy with traditional high-pollution and high-energy-consumption industries has revitalized these sectors, effectively facilitating their transition towards green development and expediting China's green economic transformation[2]. As a key means of accelerating China's green economic transformation, enterprise green technological innovation has also shown more vigorous development trend under the impetus of the digital economy. The digital economy enhances the capacity and efficiency of corporate green technology innovation by integrating modern digital technologies, including artificial intelligence, cloud computing, and blockchain. Conversely, the digital economy diminishes the expenses associated with research, development, and implementation of green technology, while expediting technological advancement and market dissemination.

Most studies indicate that the advancement of digital economy, as a new driving force to enhance regional innovation capacity, plays a crucial role in fostering technological innovation. Xiong and Cai found that the robust advancement of the digital economy significantly fosters both technological and product innovation, especially in technological innovation. Dong et al.[3] identified that the digital economy enhances the technological innovation of manufacturing businesses by reducing enterprise costs, stimulating innovation dynamics and strengthening the agglomeration effect. Cao et al.[4] explored the influence of digital economy on low-carbon development in the context of the moderating and threshold effects of green technology innovation exhibits a counter-regulatory mechanism in this process. Xie and Li[5] utilized the system GMM model to demonstrate that the digital economy fosters green technological innovation within the advanced manufacturing sector, with resource allocation optimization and industrial structure enhancement serving as significant intermediary pathways.

Furthermore, certain research studies the impact of Internet technology, digital banking and other branches of the digital economy on technological innovation. Internet technology acilitates technological innovation by reducing the cost of data collection and analysis in the process of technological innovation, and data finance alleviates the challenges of financing accessibility and costs within the conventional financial system, and provides strong financial support for corporate technological innovation. In terms of Internet technology. Hui et al.[6] examined the influence of Internet development on regional innovation capacity from three dimensions of linear, nonlinear and constraint mechanism, and found that the Internet has significantly enhanced the innovation capacity of various regions in China, especially in the western and central regions. In addition, digital transactions, such as digital finance, can effectively solve traditional financial problems and more strongly promote technological innovation. According to Wan et al.[7] discovered that the advancement of digital finance substantially alleviates the financing constraints faced by enterprises, which in turn positively influences enterprise innovation.

Through combing and analyzing the relevant literature, it is found that the existing literature has extensively explored the infulence of digital economy and its subfields on technological innovation, which also includes the examination of the impact mechanism of digital economy on green technological innovation and the moderating effect of green technological innovation. However, there are not enough studies from the more microscopic enterprise level. In view of this, this paper focuses on two major factors, namely, R&D investment and managerial capability of firms, and explores their mediating impacts on the relationship between the digital economy and green technological innovation in enterprises. The objective is to deepen research in digital economy and enterprise green technology innovation, offering practical guidance and theoretical reference for companies to improve their green technology innovation capacity and development resilience amid the dual influences of the digital economy and new technological advancements.

2. Theoretical analysis and research hypotheses

2.1. Digital economy and green technology innovation

Zhang et al.[8] found that the theory of sustainable development catalyzed the emergence of the digital economy, and the technological innovation effect of the digital economy further promotes the low-carbon, and clean development of enterprises, which can effectively mitigates pollution and environmental degradation resulting from corporate operations, thereby achieving sustainable economic development. Based on the theory of environmental Kuznets curve, the traditional economic development mode has been unable to adapt to the current situation of serious global environmental damage and energy crisis.Paul Miller[9] believes that big data analysis can help enterprises better understand t resource utilization and environmental impact, and intelligent manufacturing technology can enhance production efficiency and diminish energy consumption. Intelligent manufacturing technology enhances production efficiency and decreases energy use. The digital economy enables firms to achieve environmental protection goals while simultaneously reducing costs and enhancing efficiency, which can motivate firms to implement green technological innovation and achieve sustainable development. Based on this, this research proposes the following assumptions:

Hl: The improvement of the development level of digital economy will foster the enhancement of the level of green technological innovation.

2.2. Digital economy, R&D investment and green technology innovation

R&D investment, as the fundamental activity of firms in technological innovation, significantly contributes to the advancement of green technological innovation. Utilizing the Super-SBM model, Wang et al.[10] explored the heterogeneous effect of R&D investment on green innovation efficiency. It is found that the rapid development of the digital economy has brought more capital and market opportunities, which enabled enterprises to make better R&D investment. With the emergence of digital economy, innovative enterprises have gained more investment opportunities. The advent of venture capital, venture funds and alternative investment methods has provided more financial support for enterprises, enabling them to invest in R&D more freely. Consequently, this paper put forward hypothesis H2:

H2: Research and development investment mediates the influence of the digital economy on corporate green innovation.

2.3. Digital economy, managerial ability and green technology innovation

Managerial ability denotes the operational competence of enterprise managers, serving as a crucial foundation for improving the efficiency of resource utilization and the effectiveness of management during the organization's operation and development. The manager's capacity to propel technological innovation can enhance the output efficiency of green technological innovation propelled by the digital economy. From the perspective of technological innovation, in the process of enterprise technological innovation development, a manager's capacity to drive enterprise technological advancement is reflected in their ability to devise a rational and effective technological innovation development strategy, as well as to delineate the objectives and trajectory of technological innovation. Zhu[11] discovered that with the direction of managers' appropriate technological innovation strategies and objectives, firms may execute technological innovation operations more efficiently. During the influence of digital economy on green technological innovation, the digital economy enhances green technological innovation in enterprises by expanding green financing channels, thereby offering substantial support for such innovations. However, the utilization of funds to obtain green technology innovation results still rely upon the participation of enterprise R&D departments and the effective decision-making of enterprise managers. Therefore, the research puts forth hypothesis H3:

H3: Management competence exhibits a favorable moderating effect on the impact of digital economy on enterprise green innovation.

3. Study Design

3.1. Model Setup

3.1.1. The baseline regression model

Based on the research content of this paper, regression models were constructed as follows.

$$EnvrInvPat = \alpha_0 + \alpha_1 Score_{it} + \alpha_2 X_{it} + \lambda_i + year_t + i.ind + \varepsilon_{it} \quad (1)$$

In equation (1) above, the green technology innovation in province i (i=1,2,...,30) during the year t (t=2012,...,2022) is represented by EnvrInvPat. The digital economy level of province i in year t is represented by Score_{it}. X_{it}represents control variables. for individual fixed effects, the year_t is a time fixed effect, the $\mathrm{i.ind}$ for industry fixed effects. is a randomized perturbation term.

3.1.2. Modeling of impact mechanisms

Based on Wen Zhonglin's three-step test for mediation effect, the model was constructed as follows.

$$lnRD = \alpha_0 + \alpha_1 Score_{it} + \alpha_2 X_{it} + \lambda_i + year_t + i.ind + \varepsilon_{it} \quad (2)$$

$$EnvrInvPat = \alpha_0 + \alpha_1 Score_{it} + \alpha_2 lnRD_{it} + \alpha_3 X_{it} + \lambda_i + year_t + i.ind + \varepsilon_{it} \quad (3)$$

In the formula, the lnRDdenotes R&D investment, which is measured by the logarithm of the amount of R&D investment of enterprises after+l, and other symbols have the same meaning as in Model 1.

The moderating effect test is modeled as follows.

$$EnvrInvPat = \alpha_0 + \alpha_1 Score_{it} + \alpha_2 Score * Ability_{it} + \alpha_3 Ability_{it} + \alpha_4 X_{it} + year_t + i.ind + \varepsilon_{it} \quad (4)$$

In the formula of (4), the $\mathrm{Ability}_{it}$ Indicates managerial capacity. $\mathrm{Score} * \mathrm{Ability}_{i,t}$is the interaction term between the explanatory and moderating variables, if the coefficients of the explanatory variables in Eq.(1) are significant, in Eq.(4), the $\mathrm{Score} * \mathrm{Ability}_{i,t}$ If the coefficients are significant and have the same sign as the coefficients of the explanatory variables in Eq.(1), it indicates that the increase of the moderating term can effectively strengthen the effect of the explanatory variables on the explanatory variables; if they are both significant and have the opposite sign, it indicates that the increase of the moderating term will inhibit the effect of the explanatory variables on the explanatory variables.

3.2. Variable Description

3.2.1. Explained variable: green technology innovation

The explained variable of this paper is green technology innovation, based on the research results of

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Xu et al. and Wang et al., this paper adopts the quantity of green invention patents of enterprises disclosed in the CNRDS database to quantify the index of green technology innovation, and the indicators do logarithmic processing.

3.2.2. Explanatory variables: level of the digital economy

This paper's explanatory variable is the advancement of the digital economy, utilizing the indicator measurement methodology proposed by Wang et al. A total of 20 indicators are selected across four dimensions: digital infrastructure development, digital industrialization, industrial digitization, and digital innovation capacity, to establish the indicator system for assessing the regional digital economy level, which is determined using the entropy value method.

3.2.3. Mechanism variables: enterprise R&D investment, managerial capacity

In order to explore the mechanism of the influence of the digital economy on the green innovation of enterprises, this paper chooses two variables: enterprise R&D investment and enterprise managerial ability.

Firms' R&D investment is measured by taking the logarithm of firms' R&D investment, referring to the measure of Li et al.

Managerial ability, with reference to Song et al.[12], Zhu[9], Demerjian et al. and other scholars on the measurement of corporate managerial ability. Initially, utilize the DEA model to ascertain the input-output efficiency of the firm, followed by employing regression analysis of the DOBIT model to evaluate the residuals, thereby assessing the managerial capability of the enterprise. The specific calculations are detailed as follows.

Step 1: Measure the input-output efficiency of enterprises based on DEA model.

$$\max_v \theta = \frac{\text{Sales}}{V_1\text{COGS}+V_2\text{SG\&A}+V_3\text{PPE}+V_4\text{Intangible}+V_5\text{Goodwill}+V_6\text{R\&D}} \tag{5}$$

In the above formula (5), Sales is the enterprise sales, i. e. operating income, as the output variable; COGS is the enterprise operating costs; SG&A encompasses the total management and selling expenses of the enterprise; PPE is the enterprise net fixed assets; Intangible is the enterprise net intangible assets; Goodwill refers to the value of goodwill; R&D is the amount of enterprise R&D investment, and the above six indicators are used as input variables. The above six indicators are used as input variables.

After obtaining the firm's input-output efficiency θ based on the DEA model, the firm's managerial competence is further measured using the Tobit model.

Step 2: Construct a Tobit model to measure managerial competence

$$Efficiency = \alpha_0 + \alpha_1 Size + \alpha_2 MS + \alpha_3 FCF + \alpha_4 Age + \alpha_5 BHHI + i.year + \varepsilon_i \tag{6}$$

In equation (6) above, Efficiency i. e., the output efficiency θ, as measured in the previous section. serves as the intercept, while the$\alpha_1 \sim \alpha_5$is the coefficient corresponds to each variable, Size is the enterprise size variable, MS is the enterprise market share variable, FCF is the enterprise free cash flow variable. Age is the enterprise age variable, and BHHI is the enterprise business complexity variable. The BHHI is measured by the Herfindah1 index of each type of main business income of the enterprise. Utilizing the Tobit model, we fitted the model and measured the residuals to obtain the managerial competence level of enterprises, which was used as a moderator variable for further analysis.

3.2.4. Control variables

Drawing on previous research results in the literature, this paper chooses enterprise size, the asset-liability ratio, the return on equity, the proportion of inventory, the proportion of fixed assets, Tobin Q value, whether it is a loss, board size, the proportion of independent directors, the integration of two positions, the proportion of management shareholdings, the occupy of funds by major shareholders, whether it is a Big4 audit firm, listing age, nature of equity as the control variables.

4. Empirical analysis and results

4.1. Descriptive statistical analysis

Descriptive statistical analysis of the variables selected in this paper, as shown in Table 1.

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Table 1: Descriptive Statistical Analysis

Variable	Obs	Mean	Std. dev.	Min	Max
EnvrInvPat	23,202	0.605	0.952	0	4.466
Score	23,202	0.247	0.144	0.029	0.590
lnRD	23,202	0.751	0.752	0	6.212
Ability	23,202	0.679	0.074	0.531	1.202
Size	23,202	22.325	1.263	19.693	26.452
Lev	23,202	0.420	0.195	0.035	0.916
ROE	23,202	0.056	0.138	-0.962	0.426
INV	23,202	0.132	0.104	0	0.779
FIXED	23,202	0.210	0.146	0.002	0.719
TobinQ	23,202	2.098	1.369	0.799	15.607
Loss	23,202	0.128	0.334	0	1
Board	23,202	2.117	0.195	1.609	2.708
Indep	23,202	0.377	0.054	0.313	0.600
Dual	23,202	0.294	0.456	0	1
Mshare	23,202	0.137	0.188	0	0.702
Occupy	23,202	0.014	0.021	0.000	0.189
Big4	23,202	0.056	0.229	0	1
ListAge	23,202	2.246	0.666	1.099	3.401
SOE	23,202	0.312	0.463	0	1

Through the descriptive statistical analysis results in Table 1, we can see that the mean value of EnvrlnvPat is 0.605, the standard deviation is 0.952, indicating significant disparities among listed companies, with some exhibiting high levels while others have not engaged in green technology innovation. Score mean value is 0.247, standard deviation is 0.144, suggesting an overall relatively small but uneven development among provinces. The average lnRD is 0.751, and its standard deviation is 0.752, reflecting the existence of gaps in R&D investment levels overall, with some companies not conducting any R&D investment. The average managerial competence is 0.679, with a standard deviation of 0.074, indicating an overall relatively small variation in managerial capabilities among listed companies, but there are also cases of both low and extremely high levels of managerial competence.

4.2. Baseline regression analysis

This article conducted regression analysis using a triple fixed effect model based on individual, time, and industry, with results presented in Table 2.

Table 2: Baseline regression results

	(1) EnvrInvPat
Score	0.239^{***}
	(2.75)
_cons	-6.845^{***}
	(-20.88)
Observations	23202
R^2	0.131
Control variables	YES
Individual fixation	*YES*
Time fixed	*YES*
Industry fixation	*YES*

t statistics in parentheses $^{*}p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$

The regression results in column (1) indicate that the influence coefficient of Score on EnvrlnvPat is 0.239, which is significant at 1% level, indicating that the growth of the digital economy can effectively promote the development of green technological innovation, and this paper's research hypothesis H1 is verified. Technology innovation development, the research hypothesis Hl is verified.

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4.3. Robustness tests

4.3.1. Endogenous Amendments

This paper addresses the issue of endogeneity by employing lagged explanatory variables from periods one and two, alongside two-stage generalized method of moments for instrumental variable estimation. The regression results show that the effect of Score on EnvrlnvPat is significantly positive, which verifies the robustness of the model to a certain extent.

4.3.2. Heteroscedasticity correction

This paper addresses the influence of heteroscedasticity on regression outcomes by employing clustering robust standard errors at the individual level for correction, alongside the Drisc/Kraay method for heteroscedasticity adjustment. It was found that the regression results were still significant, which further verified the robustness of the model.

4.3.3. Substitution of variables

The core variable replacement method is employed for robustness testing, as the volume of green patent applications, while indicative of enterprises' green technological innovation, also encompasses non-"technological" green innovations, so we further use the green utility model patent application volume of enterprises (GreenPat) as the replacement variable for robustness testing.The results indicate that the influence of the digital economy on enterprise green innovation is still significantly positive, indicating that the regression model in this paper has good robustness, and the regression results have high reliability.

4.4. Analysis of impact mechanisms

Based on the regression results of the baseline regression column (2) in Table 3, the estimated coefficient of InRD is 0.411, which is considerably positive at the 1% level, demonstrating that R&D investment significantly improves the green technology innovation ability of firms, hence validating Hypothesis H2. With the development of digital economy, enterprises can obtain more funds for R&D investment, thus injecting continuous vitality for their green technology innovation. However, compared with InRD the coefficient of Ability is negative and insignificant, which contradicts the theoretical notion of this work. This can be attributed to the notion that, among stringent environmental regulations, a company's managerial competence is important for responding to these regulations and achieving green transformation. Excessive management skill may result in business overconfidence, leading to the undervaluation of green technical innovation and a subsequent decline in the degree of such innovation. This indicates that, in certain instances, enhanced managerial competence may adversely affect green technology innovation.

Table 3: Impact Mechanism Test Results

	(1) EnvrInvPat	(2) EnvrInvPat
Score	0.239^{***}	0.173^{**}
	(2.75)	(2.02)
lnRD		0.411^{***}
		(23.57)
Ability		-0.509^{*}
		(-1.82)
_cons	-6.845^{***}	-3.231^{***}
	(-20.88)	(-9.00)
Observations	23202	23202
R^2	0.131	0.155
Control variables	YES	YES
Individual fixation	YES	YES
Time fixed	YES	YES
Industry fixation	YES	YES

4.5. Further analysis

This paper examines the influence of the digital economy on green technology innovation across different regions by creating regional dummy variables and forming an interaction term with the

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explanatory variable Score to assess regional heterogeneity, with results presented in Table 4.

Table 4: Area Heterogeneity Tests

	(1) EnvrInvPat	(2) EnvrInvPat	(3) EnvrInvPat
Score	-0.568*	0.228***	0.219**
	(-1.93)	(2.60)	(2.51)
c.Score#c.East	0.768***		
	(2.86)		
c.Score#c.Central		-0.319	
		(-0.95)	
c.Score#c.West			-1.209***
			(-3.07)
_cons	-6.823***	-6.838***	-6.836***
	(-20.81)	(-20.85)	(-20.85)
Observations	23202	23202	23202
R^2	0.132	0.131	0.132
Control variables	YES	YES	YES
Individual fixation	YES	YES	YES
Time fixed	YES	YES	YES
Industry fixation	YES	YES	YES

The regression results from the regional dummy variable interaction term, as presented in Table 4, the regression results of Column (l) indicate that the coefficient of the interaction term between the dummy variable and Score in the eastern region is positive and significant at the 1% level. This suggests that the eastern region exerts a positive moderating effect on the influence of the digital economy in fostering green technological innovation. In comparison to the central and western regions, the effect of the digital economy on the green technological innovation is much stronger in the eastern region. In comparison to the central and western regions, the digital economy in the eastern region exerts a more significant influence on green technology innovation. The regression results of column (2) and (3) indicate that the influence of digital economy on green technological innovation in the central region is not significant, while the influence of the digital economy in the western region is less pronounced than that in the central and eastern regions.

5. Conclusions and Recommendations

The conclusions of this paper are as follows: The extent of the digital economy exerts a substantial beneficial influence on green technological innovation, and an elevation in the digital economy's level can significantly augment green technological innovation; research and development investment serves as a positive mediator in the relationship between the digital economy and corporate green innovation, while the influence of managerial capability on corporate green innovation is not obvious; the impact of the digital economy on green technological innovation is most pronounced in the eastern region, followed by the western region. The impact of the digital economy on green technological innovation is most pronounced in the eastern region, whereas it is least significant in the western region.

According to the above conclusions, this study gives the following recommendations:

Primarily, enhance the development of digital economic infrastructure. The government and enterprises should increase investment in digital economy infrastructure construction, including 5G network, huge data center, cloud computing platform, etc.

Secondly, optimize the structure of R&D investment. Enterprises should pay more attention to R&D investment in the field of green technology, and at the same time, the government can further optimize the structure of R&D investment through policy guidance and financial support.

Thirdly, establish the power check and balance mechanism. Although many enterprises have achieved the independence and effectiveness of' their boards of directors and supervisory boards, they still need to be alert to the problems of collusion and power abuse.

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