Empirical Testing of Digital Finance on China's Green Technology Innovation

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Abstract. Based on panel data from 30 provinces in China from 2011 to 2021, this study uses panel regression to empirically analyze the relationship and impact of digital inclusive finance (DIF) and green technology innovation (GTI), and further explores the regulatory effect of GTI and DIF on energy conservation and environmental protection, as well as the threshold effect of financial regulation. Research was found that, firstly, DIF has a significant positive impact on GTI, and the conclusion remains valid after conducting a series of robustness tests. However, there is heterogeneity in its impact across different dimensions and regions. Secondly, DIF and GTI can effectively reduce pollution emissions, promote energy conservation and environmental protection. Thirdly, the positive promotion effect of DIF on GTI has a threshold effect. After crossing the threshold, the promotion effect of both DIF and financial regulation on GTI is enhanced.

Keywords: Digital inclusive finance; Green technology innovation; Energy conservation and environmental protection; Regulatory effects; Threshold effect.

1. Introduction

With the continuous development of urban economy, environmental pollution and climate change issues are becoming increasingly prominent (Chen et. al., 2023)[1]. Urban environmental pollution control and carbon reduction have become hot topics for scholars at home and abroad[1]. According to data from relevant departments of the United Nations, since the 19th century, a large amount of greenhouse gas emissions has caused global warming, posing a serious threat to human survival and development. From an international perspective, in 2022, G20 leaders adopted the "G20 Transitional Financial Framework" at the Bali Summit, which has profound significance for G20 members to promote financial support for high carbon emission industries, enterprises, and related economic activities to transition to green and low-carbon. Many rapidly developing regions in China have faced prominent problems such as resource depletion, environmental pollution, ecological damage, lack of freshwater resources, and greenhouse gas emissions (Yang et. al., 2023)[2]. Therefore, solving these problems is urgent, and people need new technologies to achieve energy conservation (Energy_consum) and emission reduction, and strengthen environmental protection (Enviro_protec). Green technology innovation (GTI) has been recognized as an important driving force for improving environmental quality by reducing energy intensity, improving production process efficiency, and increasing sustainable and environmentally friendly products and services (Cheng et al., 2021) [3].

With the deep popularization of mobile communication devices, the comprehensive coverage of the Internet, and the fast-development of 5G, artificial intelligence (AI), etc., huge potential of the big data era are waiting to be released (Li et. al., 2023) [4]. Massive data, as internal data generated by enterprises, contains important value in production and operation processes. Digital inclusive finance (DIF) utilizes high-tech means like big data, blockchain, the Internet, and the Internet of Things to enhance the operational rules of traditional banks through electronic services. It solves the problems of geographical limitations, outdated payment methods, and information asymmetry in traditional finance, effectively improving the integrity, authenticity, and accuracy of financial data. it also portraying more accurately in customer credit, greatly improve customer service level and risk control capabilities. Over the past decade, China's level of financial inclusion has experienced rapid growth. Therefore, the digital economy and digital finance brought about by the Internet revolution can benefit groups that were previously excluded from traditional finance and credit reporting, thereby improving the accessibility and inclusiveness of finance (Zhang et. al, 2019)[5].

This study uses the number of green patent applications and DIF in China from 2011-2021 to empirically test the effect of DIF on GTI, discusses the impact mechanism of DIF and GTI from regional and economic aspect of heterogeneity. Meanwhile, this study deeply tests the difference in the effect of the three dimensions of DIF, coverage, depth of use and digital degree, on GTI. GTI faces many uncontrollable factors during the incubation and start-up period. First of all, it is difficult to accurately calculate the balance between project revenue and financing. Next, the relationship between input and output is often due to insufficient market recognition and marketing efforts of products, resulting in revenue not meeting expected valuations. Last but not least, R&D costs continue to increase with the R&D cycle, moreover, many science and technology innovation enterprises are hard to acquire financing and expensive. These make it difficult for its own funds to continue the funding for research and development of GTI. By coincidence, digital finance has typical network and inclusive characteristics, naturally carrying advantages such as low threshold, fast speed, broad coverage, and high efficiency (Han et. al, 2023)[6]. Digital finance has broken the data gap between B2B, C2C, and B2C, building the information communication bridge between different customers, effectively solving the problem of information asymmetry, quickly solving the accurate portrayal of customers by financial institutions, and indeed solving the financial matter in the corporation.

Compared with existing literature, this study tries to make some contributions in the following areas: firstly, this study studies the direct impact of DIF on GTI. DIF has a significant promoting effect on GTI, but its impact has differences across different regions and dimensions. Secondly, this study provides important research insights. The study discussing the role of the GTI and DIF in Energy_consum and Enviro_protec, and enriching existing relevant research.Thirdly, the study finds the nonlinear effects of digital finance on GTI, and incorporates financial regulation into an empirical framework to provide more empirical evidence. It plays an important role in enhancing law enforcement and supervision in government departments, empowering enterprises to innovate green technology in financial institutions, and promoting the concept of green consumption in the public.

2. Literature Review and Theoretical Analysis

In terms of the interfering factors of GTI, on the one hand, environmental regulations side, strict environmental policies can encourage GTI. Different regulatory policies have different impacts on GTI, with the negative impact of the environmental responsibility system on heavily polluting enterprises being particularly significant (Tang et. al., 2020) [7]. Liu et. al., (2023) found a nonlinear relationship between environmental regulation and carbon intensity, in which GTI makes a difference. At different levels of GTI, environmental regulation has different impacts on it [8]. On the other hand, financing constraints side, GTI can reduce financing constraints. Qi et al. (2019) studied listed companies in the heavily polluting industries of the Shanghai and Shenzhen A-shares. By testing the data of these companies from 2012 to 2021, they found that GTI and environmental information disclosure have an interactive effect on financing constraints. GTI can reduce financing constraints, while high-quality environmental information disclosure can improve the transparency of corporate environmental governance [9]. The essay by Qian et al. (2020) announces that financing constraints can lead to a fund shortage of R&D for enterprises, making it difficult to carry out GTI, thereby limiting their development [10].

In response to the impact of digital finance on green related indicators, the development of digital finance has reduced the intensity of carbon emissions. Digital finance can promote industrial structure upgrading and technological innovation, thereby reducing the dependence of economic development on fossil fuels and ultimately reducing carbon emission intensity (Tang et. al., 2020) [11]. From the perspective of regional development level, the heterogeneity analysis by Li et al. (2020) shows that regions with high levels of digital finance development have a much greater impact on carbon emission intensity than regions with low levels of digital finance development. Local digital finance development has a negative spillover effect on the carbon emission intensity of neighboring regions [12]. From a dimensional perspective, the coverage and depth of digital finance have a significant

inhibitory effect on carbon dioxide emissions (Feng et al., 2023) [13]. From the perspective of environmental pollution, the development of digital finance has significant governance effects on environmental pollution. In cities with lower financial regulatory intensity, the development of digital finance can play a stronger role in reducing emissions (Zheng et al., 2022) [14].

DIF has an impact on GTI in many aspects. Firstly, promote innovation in financial products and reduce financing constraints. DIF can integrate communication technology with financial service models such as payment and credit. Financial institutions can use digital finance to innovate green financial products and service models, coordinate the use of green credit, green bonds, green funds and other products, enrich the variety of green financial bonds, expand the sources of green funds, explore the development of green finance and climate friendly financing models, and promote the diversification of green credit business models. Secondly, technology empowers green innovation and promotes the optimization of enterprises themselves. Enterprises are exploring and utilizing technological means such as big data, blockchain, and AI based on their actual situation, continuously improving product development, operation and sales, investment and financing management business processes, risk prevention and control, and providing support for green financial management. Furthermore, green finance need to strengthen the digital capacity construction, improve the level of informatization, intensive management, and service, continue to promote the transformation of office "online and intelligent", and technology will assist paperless operations and services. Thirdly, promote industrial Energy_consum and Enviro_protec. Domestic and foreign scholars have found that technological innovation has a driving internal impact on the high-quality development of industry economy and the optimization and upgrading of industrial structure. For industries such as mining and construction with high pollution and energy consumption, digital finance can help them achieve technological progress and faster green transformation and optimize industrial layout.

3. Model and data

3.1 Establishment of econometric models

Aim to test the effect of DIF on GTI, this study structure the following benchmark regression econometric model, as shown in equation (1):

$$Greetechin\_no_{i,p,t} = \alpha_0 + \alpha_1 Index\_aggregate_{p,t} + \alpha_2 x_{i,p,t} + \rho_t + \omega_p + \varepsilon_{i,p,t} \quad (1)$$

Among them, the dependent variable GTI represents green technology innovation, the core explanatory variable DIF represents the digital inclusive finance index, which α_0 means a constant term and α_1 is the estimated parameter of the core explanatory variable. When α_1 is greater than 0, it indicates that the development of digital finance promotes GTI. The $x_{i,p,t}$ is the control variable and the α_2 core explanatory variable. This study adopts a fixed effects model, which ρ_t represents time fixed effects and ω_p represents regional fixed effects. Represents a random perturbation term.

To test the impact of DIF and GTI on Energy_consum and Enviro_protec, based on equation (1), this study introduces the interaction terms of "energy consumption intensity", "per capita energy consumption", "sulfur dioxide emission intensity", and "per capita sulfur dioxide emission", and constructs the following regulatory effect model, as shown in equation (2), (3), (4), and (5):

$$Energy\_consum\_intensity_{i,p,t} = \beta_0 + \beta_1 Greagg_{p,t} + \beta_2 Greetechin\_no_{p,t} + \beta_3 Index\_aggregate_{p,t} + \beta_4 x_{i,p,t} + \rho_t + \omega_p + \varepsilon_{i,p,t} \quad (2)$$

$$Per\_energy\_consum_{i,p,t} = \lambda_0 + \lambda_1 Greagg_{p,t} + \lambda_2 Greetechin\_no_{p,t} + \lambda_3 Index\_aggregate_{p,t} + \lambda_4 x_{i,p,t} + \rho_t + \omega_p + \varepsilon_{i,p,t} \quad (3)$$

$$So2\_emis\_intensity_{i,p,t} = \kappa_0 + \kappa_1 Greagg_{p,t} + \kappa_2 Greetechin\_no_{p,t} + \kappa_3 Index\_aggregate_{p,t} + \kappa_4 x_{i,p,t} + \rho_t + \omega_p + \varepsilon_{i,p,t} \quad (4)$$

$$Per\_So2\_emis_{i,p,t} = \gamma_0 + \gamma_1 Greagg_{p,t} + \gamma_2 Greetechin\_no_{p,t} + \gamma_3 Index\_aggregate_{p,t} + \gamma_4 x_{i,p,t} + \rho_t + \omega_p + \varepsilon_{i,p,t} \quad (5)$$

Among them β_0, λ_0, κ_0 and γ_0 represent constant terms, and β_1, λ_1, κ_1, ρ_1 and β_2, λ_2, κ_2, ρ_2 and β_3, λ_3, κ_3, ρ_3 and β_4, λ_4, κ_4, ρ_4, all represent unknown regression coefficients. Energy_ Consum_ In represents "energy consumption intensity," per_ Energy_ Consum represents "per capita energy consumption", So2_ Emis_ In represents "sulfur dioxide emission intensity", Per_ So2_ Emis stands for "per capita sulfur dioxide emissions". Other variables follow the above explanation.

3.2 Variables and data

3.2.1 Explanatory variable:

GTI. This study chooses a broader and more comprehensive indicator of the number of green invention applications and the number of green utility model applications. The sum of the two is used to construct a new indicator of the number of green patent applications, and then they are averaged and logarithmically measured to measure GTI. This value is positively correlated with the standard of GTI.

3.2.2 Core explanatory variables:

DIF. The study selects the "Peking University Digital Inclusive Finance Index" compiled by the Peking University Digital Finance Research Center to measure the development status of digital finance in various provinces of China and conducts research by taking logarithms of it. This value is positively correlated with the level of DIF and can be used to observe the development level of digital finance in different regions and years from multiple dimensions.

3.2.3 Control variables:

This study selects the following six control variables from the perspectives of government, industry, and pollution: government intervention (Gov_interven), represented by the ratio of general budget expenditure to GDP. The proportion of the secondary industry (Pro_secon_industry), the ratio of added value of the secondary industry to GDP. Per capita gross domestic product (Per_GDP), per capita GDP. Trade openness level (Trad_open_lev), expressed as the ratio of import and export value of goods to GDP. Per capita education level (Avg_age_edu), summed by the primary school population, middle school population, high school population, and college and above population, then divided by the population aged six and above. And industrial pollution control investment (Inv_ind_pol_contr), expressed as the investment completed in pollution control projects. The above control variables are all logarithmic.

3.2.4 Adjusting variables

This study uses the product of logarithmic GTI and logarithmic DIF as the moderating variable. The higher the indicator, the greater the promoting effect of GTI and DIF on Energy_consum and Enviro_protec.

3.2.5 Threshold variables

This study selects the DIF and the Financial Regulatory Expenditure Index (Fin_regul) as threshold variables. The processing method for DIF is the same as above. The financial supervision expenditure index is created as the ratio of financial supervision and other affairs expenditure to general budget expenditure. The above threshold variables are all logarithmic.

3.2.6 Tool variables

The number of internet broadband access ports (Inter_accport). There is a natural connection between DIF and the internet. This study selects the logarithmic number of internet broadband access ports as the instrumental variable.

3.2.7 Data selection

This study selects 30 provinces in China in the 11 years from 2011-2021 (according to the availability and integrity of data, this study excludes Hong Kong, Macao, Taiwan and Tibet) as research samples, and then constructs panel data. In addition, data of energy consumption in the past

two years are missing and they are estimated by the power consumption with complete data. The DIF in this study is sourced from the Digital Finance Research Center of Peking University. The control variables, moderating variables, threshold variables, and instrumental variables are sourced from the China Statistical Yearbook, China Environmental Statistical Yearbook, China Energy Statistical Yearbook, and China Science and Technology Statistical Yearbook. The green patent application data is compiled from the China Data Service Platform. Use Stata 17.0 to preliminarily organize and analyze the original data.

Table 1. Variable Declaration

Variable type	Variable	Variable Declaration
Explained Variable	Green technology innovation (GTI)	Number of green invention applications+number of green utility model applications=number of green patent applications
Core explanatory variables	Digital Inclusive Finance Index (DIF)	Logarithmic "Peking University Digital Inclusive Finance Index"
Control variable	Government intervention (Gov_interven)	Ratio of logarithmic general budget expenditure to GDP
	The proportion of the secondary industry (Pro_secon_industry)	Ratio of added value of logarithmic secondary industry to GDP
	Per Capita GDP (Per_GDP)	Log Gross Domestic Product divided by Total Population
	Trade openness level (Trad_open_lev)	The ratio of logarithmic goods import and export amount to GDP
	Per capita education level (Avg_age_edu)	Logarithmic (primary school population+middle school population+high school population+college and above population)/population of six years old and above
	Investment in industrial pollution control (Inv_ind_pol_contr)	Investment completed for logarithmic pollution control project
Adjusting variables	Adjusting variables (Greagg)	lnDIF*lnGTI
threshold variable	Financial regulatory expenditure index (Fin_regul)	Ratio of expenditure on logarithmic financial supervision and other affairs to general budget expenditure
Instrumental variable	Number of internet broadband access ports (Inter_accport)	Number of logarithmic internet broadband access ports

4. Empirical Result Analysis

4.1 Descriptive analysis

Table 2 shows the descriptive statistical results of the raw data of the main variables in the study: the minimum and maximum values of the provincial level DIF is 18.3300 and 458.9700, respectively, with the maximum value exceeding ten times the minimum value. There are significant regional differences in the degree of DIF in China, and the other three dimensions also show the same situation. The overall value of GTI is relatively small, indicating that China's GTI still needs to be developed.

Table 2. Descriptive Statistics of Main Variables

	OBS	Mean	Sd	Min	Max
DIF	330	231.4727	103.3132	18.3300	458.9700
GTI	330	0.1405	0.1909	0.0040	1.3593
Gov_interven	330	0.2487	0.1025	0.1066	0.6430
Pro_secon_industry	330	0.4266	0.0877	0.1580	0.5900
Per_GDP	330	58566.85	28895.26	16413.00	183980.00
Trad_open_lev	330	0.2653	0.2908	0.0076	1.5482
Avg_age_edu	330	9.3066	0.8984	7.5887	12.6811
Inv_ind_pol_contr	330	215368.5	210878.2	476.0	1416464.0
Coverage_breadth	330	212.9815	103.7192	1.9600	433.4200
Usage_depth	330	226.7989	105.7905	6.7600	510.6900
Digitization_level	330	301.0335	117.3561	7.5800	462.2300

Note: The above variables are all taken as raw values that have not been processed, and all variables will be logarithmically processed for empirical analysis in the following text.

4.2 Benchmark regression analysis results

This study uses a fixed effects model to study the impact of DIF development on GTI. The benchmark regression results are shown in Table 3: column (1) only includes government intervention (Gov_interven) as a control variable, and the regression coefficient of the DIF on GTI is 0.5806, which is significantly positive at the 1% level. The development of digital finance has a significant positive promoting effect on the level of GTI in enterprises. Column (2) adds other two control variables, the proportion of the secondary industry (Pro_secon_industry) and per capita gross domestic product (Per_GDP) , and the regression coefficient changes very little and is still significantly positive at the 1% level. The above conclusion is still valid. In columns (3) and (4), adds other three indicators, namely trade openness level (Trad_open_lev), per capita education level (Avg_age_edu), and industrial pollution control investment (Inv_ind_pol_contr), on GTI was added in sequence. Their regression coefficients were significantly positive at the 1% level, which more comprehensively explained the promoting effect of digital finance development on GTI in enterprises.

Table 3. Benchmark Regression Results

	GTI(1)	GTI (2)	GTI (3)	GTI(4)
DIF	0.5806*** (2.86)	0.5820*** (2.73)	0.5778*** (2.80)	0.5822** (2.76)
Gov_interven	0.2213 (0.84)	0.6782 (1.32)	0.7281* (1.52)	0.7252 (1.15)
Pro_secon_industry	-	0.7118* (1.59)	0.8182* (1.88)	0.8123* (1.89)
Per_GDP	-	0.3561 (0.69)	0.3332 (0.65)	0.3275 (0.64)
Trad_open_lev	-	-	-0.1893** (-2.00)	-0.1908** (-2.00)
Avg_age_edu	-	-	-0.5958 (-0.60)	-0.6047 (-0.61)
Inv_ind_pol_contr	-	-	-	0.0081 (0.28)
time effect	YES	YES	YES	YES
Regional effects	YES	YES	YES	YES
Constant term	-5.4794 (-6.61)***	-8.0043 (-1.64)*	-6.6062 (-1.59)*	-6.6482 (-1.61)*
R2 square	0.9104	0.9156	0.9192	0.9193
Obs sample size	330	330	330	330

Note: 1. The values in parentheses are t-statistics; * * *, * * * And * represent significant levels at 1%, 5%, and 10%, respectively. Same below

() are the t-values clustered to the provincial level.

4.3 Robustness test results

The data results show that DIF has a significant contribution to GTI. Three robustness testing methods will be used to demonstrate the robustness and effectiveness of benchmark regression results.

4.3.1 Lagging the DIF by One Phase

Due to the lag in the impact of DIF on GTI, which means that the promoting effect of DIF may not be reflected in the current year's data, but it will affect the next year's data. Therefore, this study conducts regression tests on the benchmark model after one period of lag in DIF. The regression results are shown in column (1) of Table 4. The research results indicate that DIF still has a significant promoting effect on GTI after a lag period, and the results of other control variables have little change compared to before the lag period.

4.3.2 Replace GTI Metrics

Due to the lack of a unified standard for measuring GTI, this study replaces the logarithmic per capita number of green patent applications with the logarithmic number of green patent applications for stability testing. The regression results are shown in column (2) of Table 4. The research results show that the regression coefficient is significantly positive at the 5% level, slightly decreasing compared to the results after per capita, but still positive. This indicates that regardless of whether the number of green patent applications is per capita or not, DIF has a significant promoting effect on them.

4.3.3 Estimation of instrumental variables

Considering the close correlation between DIF and the internet, this study selects the number of internet broadband access ports (Inter_accport) as the instrumental variable and uses the least squares method for regression. The Internet is highly related to DIF, and internet port access is a necessary condition for conducting digital financial activities. Digital finance is an application derived from social and economic aspects based on the support of internet technology, and the correlation is met. The F-statistic is 224.60, which is much greater than 10, and the corresponding p-value is much less than 0.01, indicating the absence of weak instrumental variables. The empirical results are shown in column (3) of Table 4, with a regression coefficient of 1.8454, which is significantly positive at the 5% level. The results indicate that the number of internet broadband access ports still has a significant positive impact on GTI.

Table 4. Robustness Test Results

	Lagging for one period	Replace Variables	Instrumental variable method
DIF	0.4720*** (4.14)	0.5192** (2.41)	1.8454*** (3.40)
Gov_interven	0.8312*** (3.89)	0.6947 (1.38)	0.8132*** (2.54)
Pro_secon_industry	0.7734*** (2.93)	0.9483** (2.06)	0.9001*** (3.28)
Per_GDP	0.4050* (1.90)	0.3902 (0.74)	0.1993 (0.75)
Trad_open_lev	-0.2043*** (-3.60)	-0.2070** (-2.13)	-0.1927*** (-3.18)
Avg_age_edu	-0.6009 (-0.73)	-0.6225 (-0.63)	-0.4218 (-0.45)
Inv_ind_pol_contr	0.0034 (0.15)	0.0072 (0.23)	0.0363 (1.15)
time effect	YES	YES	YES
Regional effects	YES	YES	YES
Constant term	-6.5936*** (-2.44)	3.4767 (0.83)	-8.9010*** (-2.56)
Cragg-DIF	-	-	34.122
R2	0.9022	0.9190	-
Obs	300	330	330

4.4 Heterogeneity analysis

4.4.1 Different dimensions of DIF

Aim to consider the results of different dimensions of DIF, this study studied the coverage, depth of use, and degree of digitization of DIF, as shown in columns (1) to (3) of Table 5. The coefficients of the three dimensions are 0.2609, 0.4256, and -0.2982, respectively. The research results show that the coverage and depth of DIF are significantly positive, while the degree of digitization is significantly negative. This mainly indicates that the effect of DIF over GTI mainly comes from the breadth of coverage and depth of use. This may be because the breadth of coverage and depth of use of DIF is conducive to the extension of DIF to a wider group, and more diversified financial tools and

products attract more investors to join, making the financing channels for GTI broader. However, the current digitization level and quality of DIF are not high enough to meet the needs of GTI.

Table 5. Heterogeneity Test of Dimensions

	GTI(1)	GTI (2)	GTI (3)
Coverage_breadth	0.2609*** (3.07)	-	-
Usage_depth	-	0.4265** (2.46)	-
Digitization_level	-	-	-0.2982** (-2.69)
Gov_interven	0.6580 (1.35)	0.8197* (1.72)	0.6558 (1.27)
Pro_secon_industry	0.8161* (1.88)	0.8477** (2.06)	0.7999* (1.81)
Per_GDP	0.2467** (0.46)	0.5075 (1.00)	0.3966 (0.74)
Trad_open_lev	-0.1838** (-2.03)	-0.1655* (-1.65)	-0.1924* (-1.83)
Avg_age_edu	-0.5954 (-0.61)	-0.7365 (-0.73)	-0.6911 (-0.67)
Inv_ind_pol_contr	0.0094 (0.33)	0.0055 (0.19)	0.0071 (0.28)
time effect	YES	YES	YES
Regional effects	YES	YES	YES
Constant term	-4.6597 (-1.06)	-7.4908* (-1.78)	-4.0735 (-0.90)
R2	0.9208	0.9189	0.9166
Obs	330	330	330

4.4.2 Regional heterogeneity and economic level heterogeneity

Table 6. Heterogeneity Test by Region and Economic Level

	Eastern	Central section	Western	Developed region	Underdeveloped areas
DIF	0.7134*** (3.06)	-0.1942 (-0.47)	0.2594 (0.55)	0.4323*** (3.09)	0.0381 (0.09)
Gov_interven	1.820** (2.72)	-0.3718 (-0.52)	-0.3400 (-0.45)	1.4480** (2.57)	-0.6720 (-1.13)
Pro_secon_industry	-0.4913 (-0.60)	1.2805** (2.35)	1.1491* (1.69)	0.1076 (0.19)	1.4203*** (3.13)
Per_GDP	1.5925*** (3.24)	-0.3208 (-0.52)	-1.4573** (-2.23)	0.8374 (1.25)	-0.7137 (-1.11)
Trad_open_lev	-0.2443 (-0.76)	-0.060 (-0.47)	-0.2856*** (-3.00)	-0.0146 (-0.11)	-0.1950** (-2.16)
Avg_age_edu	-3.2064* (-1.73)	-3.2571* (-1.96)	-0.1601 (-0.15)	-0.4913 (-0.28)	-2.3041* (-1.91)
Inv_ind_pol_contr	-0.030 (-1.15)	0.0428* (1.57)	0.0633* (1.44)	0.0151 (0.53)	-0.0123 (-0.31)
time effect	YES	YES	YES	YES	YES
Regional effects	YES	YES	YES	YES	YES
Constant term	-12.7232*** (-2.99)	6.6535 (1.20)	9.0176 (1.26)	-10.1995** (-2.27)	7.4900 (1.33)
R2	0.9159	0.9687	0.9424	0.9151	0.9446
Obs	121	88	121	165	165

Due to uneven development among regions, there are differences in the level of economic development among different regions. According to different geographical locations, this study vertically divides China into three regions: East, Middle, and West. Columns (1), (2), and (3) in Table 6 show the results of regional regression: in the eastern region, the coefficient of the DIF, 0.7134, is

significant at the 1% level. In the western region, the coefficient of the DIF is 0.2594. But in the middle region, the coefficient of the digital finance index is -0.1942. This indicates that the eastern region has a superior geographical location, flat terrain, complete infrastructure construction and convenient trade bring to good conditions for GTI. However, due to policies, economic levels, geographical environment, and other reasons, the promotion effect of DIF on GTI in the middle and western regions is not significant.

In addition, aim to further consider the results of the DIF, this study divides 30 provinces into developed and underdeveloped regions based on per capita GDP. Columns (4) and (5) of Table 6 show the results of regression by economic level: the coefficient of the DIF in developed regions is 0.4323, which is significant at the 1% level, while in underdeveloped regions, the coefficient is 0.0381 and not significant. This may be due to the higher economic level in developed regions, more comprehensive policies on green innovation, and higher penetration of DIF, which makes the promotion effect of DIF on GTI more significant.

4.5 Analysis of regulatory effects

To test the moderating effect of DIF and GTI on Energy_consum and Enviro_protec, based on a benchmark regression model, this study introduces an interaction term $Greagg$ between GTI and DIF, where $Greagg$ is the product of GTI and DIF. This study chooses energy consumption and sulfur dioxide emissions to reflect the energy-saving and Enviro_protec situation. Energy is the driving force behind social and economic development, affecting various industries in human society and effectively reflecting the energy-saving situation of the entire society. Sulfur dioxide, as a major atmospheric pollutant generated by industrial activities, can better reflect Enviro_protec situation. Among them, Energy consumption intensity (Energy_consum_ inten) is the ratio of total energy consumption to GDP, Per capita energy consumption (Per_energy_consum) is the per capita result of total energy consumption, Sulfur dioxide emission intensity (So2_emis_inten) is the ratio of total sulfur dioxide emissions to GDP, and Per capita sulfur dioxide emissions (Per_So2_emis) is the per capita result of total sulfur dioxide emissions.

Table 7. Test of regulatory effects

	Energy_consum_ inten(1)	Per_energy_consum (2)	So2_emis_inten (3)	Per_So2_emis(4)
DIF	-0.3957** (-2.71)	-0.3298** (-2.33)	-2.3188*** (-2.88)	-2.2527*** (-2.77)
GTI	0.3535*** (4.85)	0.3224*** (4.50)	2.0735*** (3.39)	2.0422*** (3.33)
Greagg	-0.0577*** (-4.65)	-0.0528*** (-4.37)	-0.3642*** (-3.27)	-0.3593*** (-3.21)
Gov_interven	0.0106 (0.09)	0.0777 (-0.68)	-0.3134 (-0.69)	-0.4017 (-0.91)
Pro_secon_industry	0.2323* (1.87)	0.1923* (1.54)	0.3638 (0.65)	0.3239 (0.57)
Per_GDP	-0.9966*** (-7.68)	-0.0946 (-0.75)	-1.4153*** (-2.83)	-0.5133 (-1.04)
Trad_open_lev	0.0231 (0.69)	0.0147 (0.45)	-0.0019 (-0.02)	-0.0102 (-0.08)
Avg_age_edu	-0.1310 (-0.38)	0.0108 (0.03)	-1.2870 (-1.01)	-1.1449 (-0.91)
Inv_ind_pol_contr	0.0061 (0.86)	0.0093 (1.31)	0.0573 (0.98)	0.0604 (1.04)
time effect	YES	YES	YES	YES
Regional effects	YES	YES	YES	YES
Constant term	12.7800*** (9.70)	3.7747*** (3.01)	31.9124*** (3.78)	22.9062*** (2.72)
R2	0.9067	0.6299	0.9470	0.9220
Obs	330	330	330	330

Table 7 reports the test results of the moderating effect: in terms of energy consumption, the coefficients of the interaction terms in columns (1) and (2) are -0.0577 and -0.0528, respectively, which are significant at the 1% level. The test results show that GTI and DIF significantly reduce energy consumption and have a positive moderating effect on reducing energy consumption. In terms of sulfur dioxide emissions, the coefficients of the interaction terms in columns (3) and (4) are -0.3642 and -0.3593, both significant at the 1% level. The test results also indicate that GTI and DIF have significantly reduced sulfur dioxide emissions, and still have a significant negative impact on sulfur dioxide emissions. The main reason for this may be the digitalization, networking, and intelligent transformation of enterprises, which has reduced the energy required for production and business activities. In addition, the application and transformation of advanced production, Energy_consum, and Enviro_protec process technology have reduced the emissions of industrial waste such as sulfur dioxide, both of which play an important role in Energy_consum and Enviro_protec.

4.6 Threshold effect analysis

This study tests and estimates the corresponding threshold values under the assumption of double thresholds, and the results are shown in Table 8. When the DIF and financial regulatory expenditure index (Fin-regul) are used as threshold variables, the impact of DIF on GTI shows a significant dual threshold effect. Column (1) in Table 8 provides the threshold estimation results for DIF. When DIF is below the first threshold value of 4.3800, after crossing the first threshold value, and after crossing the second threshold value of 5.4500, the coefficients are all positive and pass the significance test at the 1% level. Therefore, the promoting effect of DIF on GTI shows a form of first decreasing and then increasing. This may be because in the development process of DIF, it takes some time to blend in with GTI. With the improvement of the development level of DIF, it is increasingly able to adapt to the needs of GTI, thereby better improving GTI.

Table 8. Threshold Effect Analysis

	D=DIF	D=Fin_regul
DIF<4.3800	0.5551*** (3.88)	-
4.3800<DIF<5.4500	0.4745*** (3.81)	-
DIF>5.4500	0.5105*** (3.95)	-
Fin_regul<-6.7648	-	0.2446*** (2.93)
-6.7648<Fin_regul<-6.7582	-	0.1268 (0.99)
Fin_regul>-6.7582	-	0.2544*** (3.04)
Gov_interven	1.1092*** (3.38)	1.4476*** (5.12)
Pro_secon_industry	-0.1201 (-0.31)	-0.5228 (-1.30)
Per_GDP	1.1033*** (3.55)	1.5909*** (6.12)
Trad_open_lev	-0.2031** (-2.25)	-0.1907* (-1.83)
Avg_age_edu	0.4832 (0.45)	0.5686 (0.49)
Inv_ind_pol_contr	-0.0468*** (-2.59)	-0.0648*** (-3.48)
Constant term	-16.5596*** (-8.43)	-20.3539*** (-9.48)
R2	0.9032	0.8999
Obs	330	330

When using the financial regulatory expenditure index (Fin'regul) as the threshold variable, GTI also exhibits a significant dual threshold effect. From column (2) of Table 8, it can be seen that when market oriented environmental regulations have not yet crossed the first threshold of -6.7648, the positive promotion effect of financial regulatory level on GTI is significantly positive; After crossing the first threshold, its influence coefficient is not significant; As the level of financial regulation crosses the second threshold of -6.7582, the positive correlation coefficient between the two increases to 0.2544 and is significant at the 1% level. This shows that in the early stages of DIF, excessive financial regulation and administrative intervention may lead to resource mismatch, thereby weakening the promoting effect of DIF on GTI. However, as the level of digital financial regulation increases, the government gradually adjusts its policies for the development of DIF, thereby strengthening the promoting effect of DIF on GTI.

5. Conclusion and suggestions

5.1 Research Conclusion

This study uses 30 provinces in China from 2011-2021 as panel data to study the effect of DIF on GTI and its mechanism. Through theoretical analysis and empirical hypothesis, come to the conclusion: first, DIF is conducive to promoting GTI, but its impact on regions with different economic levels and different dimensions is heterogeneous. Secondly, pollution emissions can be reduced through DIF and GTI, achieving Energy_consum and Enviro_protec. Finally, there is a non-linear effect of the impact of DIF on GTI. The promoting effect of DIF and financial regulation on GTI shows a form of first decreasing and then increasing.

5.2 Policy recommendations

The above research conclusions not only enrich the relevant theories of DIF and GTI, but also provide the following policy recommendations for achieving the "dual carbon" goal:

Firstly, accelerate the digital transformation of finance and strengthen regional coordinated development. One is to focus on customers and build more diverse digital financial products, so that internet technology can better serve green financial products; The second is to increase the application scenarios of DIF, promote the deep integration of networked and intelligent financial services with production and life scenarios, unleash the potential of DIF, and better enhance efficiency for GTI. At the same time, corresponding development strategies will be implemented to address the issue of imbalanced development in the eastern, middle, and western regions, emphasizing the harmony between humans and nature while developing, aim to improve the level of GTI and promote development.

Secondly, adjust the energy consumption structure and promote the green upgrading of industries. We should promote the transformation of enterprises towards advanced, intelligent, and digital directions, introduce energy-saving and environmentally friendly process technologies, actively develop renewable and low-carbon energy such as solar energy, wind energy, and bioenergy, and increase basic research on cutting-edge green, low-carbon, and waste free technologies, promote the transformation of industrial structure towards high-end, and promote the overall greening of industrial structure.

Thirdly, improve the financial regulatory system and strengthen security guarantees. By utilizing modern technological means, strengthening macro prudential management, intelligent risk control management mechanisms, and grasping the balance between reducing financial risks and promoting the prosperity and development of DIF.

References

[1] CHEN X.,DI Q.,JIA W.,et al.Spatial correlation network of pollution and carbon emission reductions coupled with high-quality economic development in three Chinese urban agglomerations[J].Sustainable Cities and Society,2023,94:104552.

[2] Yang.F, Zhen. J. Relationship Between Pollution and Carbon Reduction and Economic Growth in Typical Regions Under the 'Dual Carbon' Goals: A Case Study on Urban Agglomeration in the Yellow River Basin [J/OL]. Environmental Science Research: 1-19 [2023-08-21].

[3] Cheng,Y., Yao, X. and Du K.,Environmental regulation, green technology innovation, and industrial structure upgrading: The road to the green transformation of Chinese cities[J]. Energy Economics, 7, 2021: 105247.

[4] Li.A., Xu.W., Shi.Y Research on multi-source heterogeneous big data fusion based on "physics - reason - human theory" [J]. Journal of the Chinese Academy of Sciences, 2023,38 (08): 1225-1233.

[5] Zhang.X, Wan.G., Zhang.J., et al. Digital Economy, Inclusive Finance, and Inclusive Growth [J]. Economic Research, 2019,54 (08): 71-86.

[6] Han.X., Zheng.Z., Song.W., et al. Research on the Dynamic Influence of Digital Finance on Green Technology Innovation Under Environmental Regulation [J]. Journal of Management, 2023,20 (08): 1180-1188.

[7] Tang.S, Wu.X., Zhu.J Digital Finance and Enterprise Technology Innovation: Structural Characteristics, Mechanism Identification, and Differences in Effects under Financial Regulation [J]. Management World, 2020,36 (05) 52-66.

[8] Liu.X., Zhuang.J. Environmental regulation, green technology innovation, and carbon intensity under the "dual carbon" goal [J]. Statistics and Decision, 2023,39 (13): 101-105.2023.13.018.

[9] Qi.H., Li. Z. Measurement and Evaluation of the Development Level of Inclusive Finance in China: A Micro Empirical Study Based on Different Target Groups [J]. Quantitative Economic, Technological and Economic Research, 2019,36 (5): 101-117.

[10] Qian.H., Tao.Y., Cao.S.W, et al. Theoretical and Empirical Study on the Development of Digital Finance and Economic Growth in China [J]. Quantitative Economic and Technological Economic Research, 2020,37 (6) 26-46.

[11] Tang.S., Xu.C., Zhu.J. Digital Finance and Enterprise Technology Innovation - Structural Characteristics, Mechanism Identification, and Differences in Effects under Financial Regulation D1. Management World, March 26, 2022 (5): 52-66.

[12] Li.Q., Xiao.Z. Heterogeneous Environmental Regulation Tools and Green Innovation Incentives for Enterprises: Evidence from Green Patents of Listed Enterprises [J]. Economic Research, 2020,55 (9): 192-208.

[13] Feng.S., Xu.D., Zhang.R. How does the Development of Digital Finance Reduce CO2 Emissions? —— Empirical Analysis Based on Prefecture-level Cities [J]. Contemporary Economic Science, 2023,45 (04): 15-28.

[14] Zheng.W., Zhao.H., Zhao.M. Is the development of digital finance conducive to environmental pollution control—— Discussion on the Regulating Role of Local Resource Competition [J]. Industrial Economy Research, 2022 (01): 1-13.