Journal of Innovation & Knowledge 8 (2023) 100382

Journal of Innovation & Knowledge

https://www.journals.elsevier.com/journal-of-innovation-and-knowledge

Does the development of digital inclusive finance improve the enthusiasm and quality of corporate green technology innovation?

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ARTICLE INFO

Article History:
Received 9 November 2022
Accepted 9 May 2023
Available online 16 May 2023

Keywords:
Innovation
Digital inclusive finance
Green technology
Fixed effects model
Threshold effects model

JEL:
C33
D83
G38
M11
O31

ABSTRACT

Clarifying the impact of digital inclusive finance (DIF) on green technology innovation is of great practical significance to promote the high-quality development of the green economy in developing countries. In contrast to existing research, this paper conducts a comparative study from the perspectives of innovation enthusiasm and innovation quality and creatively measures the latter based on the annual number of citations of green patents. On this basis, this paper takes Chinese A-share listed companies and the DIF index from 2011 to 2020 as the research objects, finding that the development of DIF has a more significant impact on the quality of green technology innovation than enthusiasm. The characteristics of the external environment, including financial supervision and financing constraints, may have different impacts on the innovation-driven effect of DIF, so the moderating effect model and the threshold model are used to analyze them. In particular, when the government's financial supervision intensity value for DIF is between 0.0024 and 0.0025, financial security can be taken into account, and the high-quality development of green technology can be achieved. In terms of enterprise characteristics, state-owned enterprises and enterprises that do not have a combination of general managers and chairmen can significantly achieve the green innovation-driven effect of DIF. For pollution-intensive enterprises, government supervision is necessary to help them achieve high-quality development of green technology innovation. This study provides policy implications for developing countries around the world to achieve green development by promoting the DIF level.

Introduction

Innovation is a process in which entrepreneurs recombine factors of production and establish a new production function (Schumpeter, 1934). Technological progress is an important inherent logic of economic development. However, this process continues to consume natural resources and destroy the social environment. Therefore, the "green" attribute of the technological innovation process is particularly important. Specifically, while eliminating the disadvantages of high input, high consumption and high pollution under the traditional development model, this kind of progress can continuously improve the utilization rate of resources and accelerate the optimization of industrial structure and energy structure to achieve sustainable economic and social development. Furthermore, the continuous promotion of green technology innovation is conducive to promoting environmental protection and pollution control and improving the living environment of urban and rural residents. It can help countries around the world reduce carbon emissions and make positive contributions to the governance of global climate change. Green technology innovation is an important way to promote the construction of ecological civilization in China and other countries worldwide. In fact, China has always attached importance to the status of green technology innovation in national development. This is not only one of the guiding principles for China to build a manufacturing power but also an important link in the construction of national ecological civilization.[1]

However, due to the long cycle and great uncertainty of technology from R&D to production, any error during this period will mean a very high cost (Becker, 2015). Therefore, abundant financial support is an important condition for the smooth realization of technological innovation. In the face of such a huge sunk cost risk, enterprises are willing to seek the help of external financing on the basis of endogenous financing to jointly promote the innovation iteration of green technology. External financing is one of the important means to

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[1] For more information, please see document No.28 issued by the State Council in 2015 and document No.689 jointly issued by the National Development and Reform Commission and the Ministry of Science and Technology in 2019.

https://doi.org/10.1016/j.jik.2023.100382

promote the green technology innovation of enterprises. However, external financing based on green technology innovation is difficult for two reasons. First, although green technology innovation can bring economic benefits to investors in the long term, in more cases, green technology also brings benefits to the external social operation and natural environment of enterprises. These two subjects do not need to invest any cost, which is the so-called "double positive externality" (Rennings, 2000), which means that the return on investment used for green technology innovation cannot be entirely reflected in the enterprise's financial statements in the short term. In contrast, this kind of "double positive externality" leads to an "uncertainty private rate of return" for investing in green technology innovation, which in turn makes external financing more difficult. Second, the information asymmetry that usually exists between the supply and demand of funds under the traditional financial model also leads to the phenomenon of expensive and slow financing, which makes it difficult to stimulate enterprises' enthusiasm for or to promote green technology innovation.

From the perspective of financial services, the above difficulties also mean a lack of inclusive functions. Fortunately, in the past 10 years, by relying on emerging digital technologies such as the Internet of Things, cloud computing and artificial intelligence, China's financial technology has ushered in explosive growth and constantly spawned new financial service models, which has greatly improved the availability of traditional financial services and promoted the development of inclusive finance[2] in China. The combination of emerging digital technology and inclusive finance is digital inclusive finance (DIF). Compared with the traditional model, it can effectively improve the popularization and efficiency of financial services and support the "long tail effect". In addition, it can effectively alleviate information asymmetry and reduce transaction costs with its technological advantages. Combining the above two aspects, as a supplement and improvement to the traditional financial system, DIF can reduce the "uncertainty of private rate of return" mentioned above and alleviate the information asymmetry between both sides of financing, providing financial convenience for enterprises that intend to carry out green technology R&D and improving enterprises' enthusiasm and quality of innovation for green technology. Thus, it is helpful to further explore the service function of the financial system to the real economy. This has also played a "booster role" in the high-quality development of the green economy in developing countries led by China.

However, the essence of DIF is still finance, and the original risks of its system have not completely disappeared, which may have an extra negative impact on activities such as enterprise green technology innovation. Therefore, the research objective of this paper is to deeply analyze the influence of digital inclusive financial development on enterprise green technology innovation from the perspective of innovation enthusiasm and innovation quality. At the same time, this study explores the specific role of the external environment and internal characteristics of enterprises in the above process to provide a reference for the construction of ecological civilization and the development of a green economy in China and provides policy implications for developing countries around the world to achieve green development by promoting DIF.

Literature review

Development and advantages of DIF

The concept of DIF has different titles in different countries, but overall, it is the combination of fintech and financial inclusion; the former involves technical means or methods (Muneeza et al., 2018), while the latter is a channel or ultimate goal (Mhlanga, 2020). DIF is explained by the World Bank (The World Bank, 2020) as the deployment of cost-saving digital means to reach currently financially excluded and underserved populations with a range of formal financial services suited to their needs that are responsibly delivered at a cost that is affordable to customers and sustainable for providers. DIF is essentially a holistic solution to optimize the allocation of financial resources.

Of course, the level of development of DIF varies in different countries and regions. Most European countries (e.g., Germany, France, Spain, Poland) have a below-average level of DIF, and their traditional financial services are undergoing rapid transformation with the help of fintech (Pakhnenko et al., 2021). Koh et al. (2018) conclude that it is highly likely that DIF in Southeast Asian countries such as Cambodia and Myanmar will be driven by mobile network operators. In addition, Kelikume (2021) argues that the development of DIF has a significant impact on poverty reduction in African countries. Overall, the literature suggests that DIF has a significant impact on society from both the micro and macro perspectives.

From a microeconomic perspective, although the concept of DIF has been proposed for a short time in China, it has recently shown many advantages that traditional financial services lack. According to Wang and He (2020), the development of DIF in China represents more than a payment instrument because it includes three basic business formats: digital payments, digital investment and digital financing. With the support of fintech, DIF can break the restrictions of time and space on financial services and overcome the problem of information asymmetry from traditional financial inclusion (Gomber et al., 2017) to truly realize the wide coverage, low cost and high efficiency of financial services.

From a macroeconomic perspective, the development of DIF is also of great significance. First, DIF plays a significant role in promoting economic growth, and in the long run, the impact exceeds fixed capital and human capital investment (Kanga et al., 2021). Second, DIF has a significant effect on alleviating income inequality, primarily among higher-income countries and poor countries (Demir et al., 2022; Polloni-Silva et al., 2021). Finally, DIF can reduce the "vulnerability to poverty", defined as the likelihood of poverty in the future, of farmers and other people who easily return to poverty, and it can reduce the volatility of income (Wang & He, 2020), which is conducive to the stable operation and sustainable development of society.

Influencing factors of green technology innovation

Through a review of the relevant literature on green technology innovation, we find that many factors, such as telecommunications infrastructure (Tang et al., 2021), environmental regulation (Shang et al., 2022), governments' R&D funding (Guo et al., 2018), the degree of financial development (Lv et al., 2021), political competition (Deng et al., 2019), and foreign direct investment (Behera & Sethi, 2022), can significantly affect the development of green technology innovation.

In addition, many scholars have studied the relationship (from a certain perspective) between DIF and green technology innovation. Zhu and Li (2021) discussed the coordinated development between DIF and technology innovation efficiency from the perspective of agriculture. Zhao et al. (2021) found that the degree of development of DIF has a significant positive impact on small-scale enterprise innovation. Cao et al. (2021) argued that the interaction between financial development and technology innovation can significantly weaken the volatility of green growth. Li et al. (2021) also found a significant positive U-shaped nonlinear relationship between DIF and green economic growth. There are also studies focused on the relationship between fintech and green technology innovation (or green growth) that suggest that fintech can alleviate information

[2] So-called inclusive finance is based on the requirements of business sustainability and equality of opportunities, and provides financial services that match the needs of all subjects of society at an affordable cost.

asymmetry and improve financial inclusion, thus promoting green innovation (Feng et al., 2022; Xue et al., 2022; Zhou et al., 2022). Considering that DIF is an important part of the digital economy, some scholars have studied it and found a significant spatial correlation between the digital economy and green technology innovation in different regions of China (Wang et al., 2022).

Through the review of the literature, we can see that the existing research results mainly demonstrate the relationship between DIF and enterprise green technology innovation in relation to a particular aspect of the problem (e.g., from the perspective of "fintech", "technology innovation", "green growth", or "digital economy"), but few scholars have discussed this issue comprehensively. In addition, most of the literature measures the concept of corporate green technology innovation using the number of green patent applications, which is relatively general and lacks a clear distinction and comparison between the enthusiasm and quality of the green technology innovation of enterprises. Finally, considering the "green attribute" of green technology innovation, the literature pays attention to environmental regulation. However, it does not consider that DIF still has risks and thus ignores the important role of financial supervision in the relationship between the two, which is of great significance for other countries in the world to guard against financial risks.

On the basis of previous studies, this paper combines the Digital Financial Inclusion Index (DIFI) with the green patent data of Chinese listed companies to evaluate the innovation-driven effect of DIF. The possible marginal contributions of this paper lie in the following. ① Compared with the existing research, this paper expands research on the relationship between the development of DIF and enterprise green technology innovation. Specifically, to meet the needs of high-quality innovation-driven development, we conduct a progressive analysis from innovation enthusiasm to innovation quality and clarify the nuances of the impact of digital inclusive financial development on the two. ② In contrast to the previous literature, the number of citations of green patents are used to measure the quality perspective of enterprise green technology innovation, and the number of applications of green patents are used to describe the enthusiasm of enterprise green technology innovation. These aspects enrich the existing research content from the perspective of variable setting. ③ To the best of our knowledge, this paper is the first to discuss the impact of digital inclusive financial development on the efficiency of enterprise green technology innovation from the perspective of financial supervision and to use the bootstrap method to find the boundary between insufficient supervision and oversupervision. ④ From internal and external perspectives, this paper compares the heterogeneous impact of digital inclusive financial development on enterprise green technology innovation, which makes the research conclusions more practical.

Theoretical analysis and research hypotheses

DIF & green technology innovation

The development of DIF involves the integration of emerging digital means and traditional financial service models. Big data, artificial intelligence and cloud computing technologies included in DIF can help financial intermediaries improve their risk analysis and management mechanism. Therefore, small and medium-sized enterprises (SMEs) that were previously unable to participate in financing activities can be included in the financial market. This means that the threshold for financing entry is lowered. DIF can also help financial intermediaries improve information processing efficiency so that the personalized financing needs of innovative enterprises can be met in a targeted manner. Therefore, the emergence of DIF breaks the "Eighty-Twenty Rule" and helps the financial market fully absorb customer groups with long-tail characteristics, which means the expansion of the financing audience.

In addition, the green credit service module in DIF is more inclined to provide credit services for enterprises with green attributes. Its business covers mining, chemical, nuclear power, photovoltaic and other fields, which is conducive to forcing the "Three High" enterprises (high pollution, high energy consumption and high water consumption) to carry out green technology transformation. If these enterprises can gradually achieve the goal of energy saving and emission reduction, then social development can take into account both economic benefits and environmental value.

The development of DIF has also given birth to a large number of new credit intermediaries that adapt to the application scenarios of modern science and technology, such as the Digital Bank, Ant Financial Services Group and Ali Small Loan. They effectively improve financing speed and reduce financing cost. The wide application of financial technology and the birth of new financial service institutions have also strengthened healthy competition among traditional financial institutions (banks, securities traders, fund companies, etc.). All of these factors reduce the financial burden of enterprises carrying out green technology innovation.

Peking University has conducted a follow-up survey on the development of DIF in China since 2011. Based on its newly released DIF index and secondary index data from 2011 to 2020, the development of DIF in China is summarized in Fig. 1.

As shown in Fig. 1, DIFI_cb, DIFI_ud and DIFI_dl represent the breadth of coverage, the depth of usage, and the degree of digitization of DIFI, respectively. China's DIF business achieved great leapforward development from 2011 to 2020. In 2011, the average of the provincial DIF index was 40.00; it increased to 220.01 in 2015 and further increased to 341.22 in 2020, nearly 9 times the amount from 10 years ago. From the above, we can see the rapid development trend of DIF in China. In terms of growth, the growth rate of the DIF index has slowed in recent years, indicating that as the development of the digital financial market becomes increasingly mature, the industry begins to transition from the stage of rapid growth to normal growth.

On this basis, we select 20 listed companies with the top 10 net assets among state-owned enterprises and private enterprises at the end of 2020 to further observe the relationship between DIF and their green technology innovation. Consistent with the previous logic, we analyze this information from the perspectives of innovation enthusiasm and innovation quality. The results are shown in Fig. 2.

In Fig. 2, we present the innovation enthusiasm of corporate green technology based on the application number of green patents, use the cited number of green patents to express the innovation quality of corporate green technology, and then make a linear fitting. Fig. 2 shows that the development of DIF can promote both, but it has a greater impact on the innovation quality of corporate green technology. Will there be a similar impact on all Chinese A-share listed companies? Based on the above analysis, this paper proposes the following hypotheses:

H1a: The development of DIF can enhance the enthusiasm and quality of the green technology innovation of enterprises.

H1b: Compared with the enthusiasm of innovation, the development of DIF has a greater impact on the innovation quality of green technology innovation in enterprises.

Financial risk & DIF

From the perspective of financial risk, due to the introduction of digital technology, the cross-contagion between different risks such as data theft and financial fraud has become more rapid with the development of DIF. This aggravates the instability and fragility of the financial system. Therefore, a financial supervision mode that keeps pace with the times is particularly important to not only

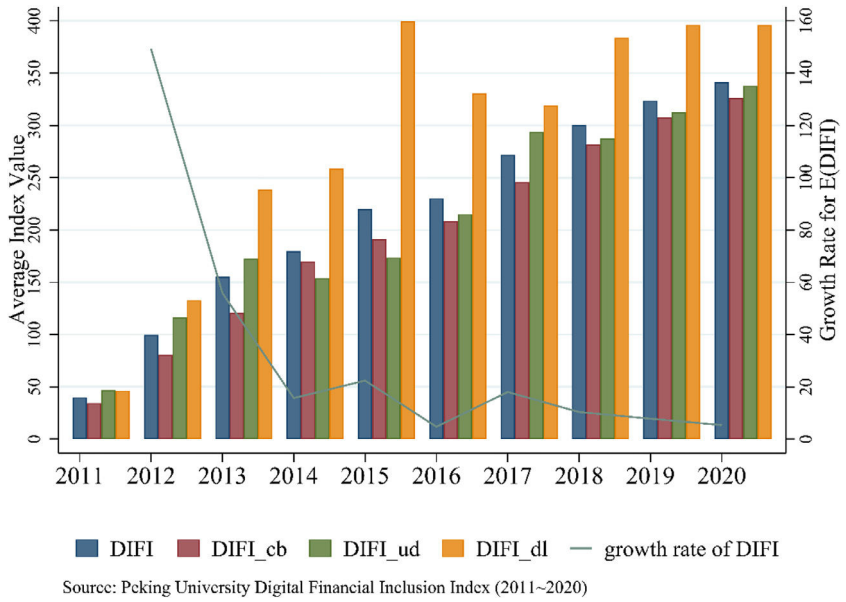

Fig. 1. Average and Growth Rate (%) of the Provincial DIFI (2011~2020).

effectively restrain the excessive innovation of financial technology (Chen et al., 2020) but also prevent nonfinancial enterprises from being distracted from their intended purpose, which enables DIF to better serve the real economy. As an important part of the incentive and supervision mechanism of technological innovation (Liu & Ma, 2021), appropriate financial risk supervision also has an incentive role. By improving the supervision mechanism of public opinion, incentives for compliance behavior can be achieved by enterprises (Peng et al., 2016), guiding the development of DIF to benefit the green technology innovation of enterprises.

In China, the relative tolerance of government regulatory departments provides a relaxed environment for the development of DIF, which is one of the important reasons why China's DIF can temporarily lead other countries around the world (Huang & Huang, 2018). However, if the financial regulation is too loose, the market order is prone to chaos and illegal operations such as moral hazard, Ponzi schemes and private data trading can be difficult to detect and deal with, which is likely to lead to the consequences of "bad money drives out good". This is obviously detrimental to financial efficiency. On the other hand, some studies show that the wider the scope of the central bank's supervision, the lower the efficiency of banks and other financial institutions, which also involves a loss of social welfare (Gaganis & Pasiouras, 2013). Moderate financial supervision can improve financial efficiency, while excessive or insufficient financial supervision can lead to its decline. Therefore, financial supervision is a double-edged sword. On the one hand, it helps to reduce the risk of the financial system and maintain financial stability and security; on the other hand, it generates additional regulatory costs, reduces the enthusiasm of enterprises for green technology innovation, and hinders the development of the green economy. Because digital finance has the characteristics of flexible and rapid technological renewal, the direction and intensity of supervision by the central bank and local government not only has a direct impact on the development of DIF (Treleaven, 2015) but also has an impact on the behavior of institutions and platforms. Blindly tightening supervision of the government and media would instead prompt the far-sighted platform to choose excessive innovation behaviors, which is not conducive to maintaining industry stability (Zhou & Chen, 2021). Based on this, we propose the following hypothesis:

H2: The change in financial supervision intensity has a threshold effect on the driving effect of the green technology innovation of DIF.

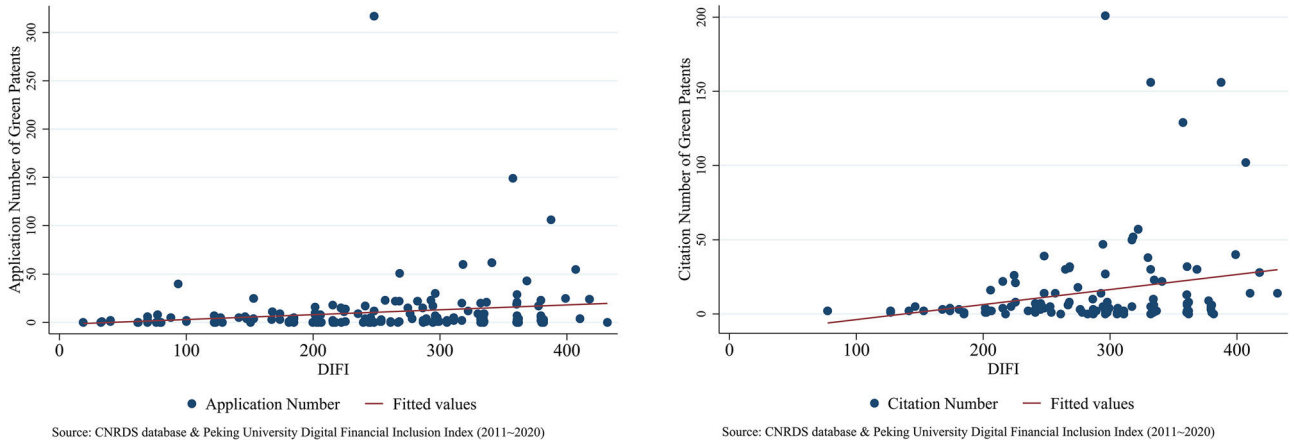

Fig. 2. Relationship between DIFI and Green Technology Innovation (2011~2020).

Materials and methods

Data source

We take Chinese A-share nonfinancial listed companies from 2011 to 2020 as the research object. The reason for choosing this sample range is that the latest DIF index update interval is 2011–2020. To ensure the persuasiveness of the sample data, the data processing steps of this paper are as follows: excluding financial industry samples; excluding samples of listed companies such as ST, *ST and PT; excluding samples of listed companies in the delisting period, suspending listing and terminating listing; excluding samples of listed companies that had been listed for less than one year for the first time by 2020; and adopting linear interpolation to complete the continuous variables with missing data. The companies' financial information variables are treated with a bilateral tail reduction of 1%. The processed samples are matched with the digital inclusive financial development index at the provincial level, and the unbalanced panel data of A-share listed companies from 2011 to 2020 are finally obtained. The DIF development index comes from the "Peking University Digital Financial Inclusion Index", the green technology innovation data of listed companies come from the Chinese Research Data Services (CNRDS) platform, and the economic characteristic data of listed companies come from the Guotai'an CSMAR database.

Variable setting

Dependent variable

The development of enterprises' green technology innovation is measured by the quantity and quality of enterprise green patents and the quantity angle represents enterprises' enthusiasm for green innovation. Since the time interval between patent application and authorization is mainly determined by the China National Intellectual Property Administration, this paper chooses the number of green patent applications (gre_pat) as one of the explained variables to eliminate the impact of exogenous variables. The quality of green technology innovation in enterprises has usually been studied through the method of "knowledge breadth" (Tao et al., 2021; Zhang & Zheng, 2018). Because this method only measures the complexity of knowledge and the extensiveness of a patent and does not fully reflect its practical value, this paper selects the annual number of citations of green patents (annu_citied) to measure the quality dimension of green technology innovation.

Independent variable

The independent variable of this paper is the development of DIF in China, and the Peking University Digital Financial Inclusion Index (DIFI) at the provincial level from 2011 to 2020 is selected as the proxy variable (Guo et al., 2020). This index is a big data index established by Ant Financial Services Group at the microuser level and has high reliability and authority. Its evaluation of the development of DIF in China is divided into three dimensions, namely, coverage breadth (DIFI_cb), depth of use (DIFI_ud) and digitization degree (DIFI_dl), which are further analyzed as subexplanatory variables in this paper. The coverage breadth of DIF mainly measures the account coverage of users of third-party payment services (e.g., Alipay service). The depth of use of DIF is mainly measured by the actual use of digital financial services[3], which includes not only indicators of the total amount of actual use (e.g., the number of people using these services per 10,000 Alipay users) but also the use of activity indicators (e.g., the number of transactions per capita, the amount of transactions per capita). In addition, the degree of digitization is an important part of the DIFI system. Specifically, more convenient digital financial services (e.g., a higher proportion of mobile payments to the total number of payments), lower cost (e.g., lower interest rates for consumer loans and small and micro business loans), and a higher degree of creditworthiness (e.g., a higher proportion of deposit-free payments to the total number of payments) all mean that the value of DIF is better reflected. Based on the above three subdimensions, DIFI contains a total of 33 specific indicators. By reducing the dimensions of these specific indicators[4], we can finally obtain the overall index.

Control variable

To overcome the influence of omitted variables as much as possible, this paper selects several variables from the perspectives of finance and governance, including the logarithm of enterprise age (age), Tobin's Q value (tobinq, measured by the ratio of market value to total assets), return on assets (roa, measured by the ratio of net profit to total assets), capital structure (lev, measured by the ratio of total liabilities to total assets at the end of the period), cash adequacy (cashflow, measured by the ratio of net cash flow of operating activities to operating income), the nature of property rights (SOE; the value of state-owned enterprises is 1; otherwise, the value is 0), the degree of equity concentration (top1, measured by the proportion of the largest shareholder), the proportion of independent directors (indratio, the proportion of independent directors to the board of directors), audit opinions (opin; the value of unqualified opinions issued by audit units is 0; otherwise, it is 1). The detailed descriptive statistical results of the above variables are shown in Table B1 in Appendix B.

Methods

According to the three assumptions mentioned above, the corresponding models are built here in turn to prepare for subsequent data analysis. Since we used annual panel data from corporations over a 10-year period, a fixed effects model is constructed as in Eq. (1) to test H1a and H1b:

$$Y_{i,t} = \alpha_1 + \alpha_2 DIFI_{i,t} + \sum \varphi CV_{i,t} + \sum Year + \sum Prov + \lambda_i + \varepsilon \quad (1)$$

where the subscript i represents the enterprise and t represents the year. The dependent variable Y represents the development of enterprise green technology innovation, separately using the number of green patents applied for (gre_pat) and the annual number of citations of green patents (annu_citied) as proxy variables. The independent variable DIFI represents the Peking University Digital Financial Inclusion Index. The symbol CV represents the control variable mentioned above. The symbol ε represents the random interference term of the model. In addition, we control the time fixed effect Year, the provincial fixed effect Prov and the individual fixed effect λ in turn.

To test H2, we construct the index spvis = regional fiscal and financial supervision expenditure (100 million yuan)/regional financial industry added value (100 million yuan), taking it as the proxy variable of financial supervision intensity (Tang et al., 2020; Wang et al., 2019), and construct a threshold regression model as in Eq. (2):

$$\begin{aligned} Y_{i,t} = {} & \pi_0 + \pi_1 DIFI_{i,t} * D(spvis \le \eta_1) + \pi_2 DIFI_{i,t} * D(\eta_1 < spvis \le \eta_2) \\ & + \pi_3 DIFI_{i,t} * D(\eta_2 < spvis \le \eta_3) + \cdots + \pi_n DIFI_{i,t} \\ & * D(\eta_{n-1} < spvis \le \eta_n) + \pi_{n+1} DIFI_{i,t} * D(spvis > \eta_n) \\ & + \sum \omega CV_{i,t} + \varepsilon \end{aligned} \quad (2)$$

[3] The digital financial services actually used are payment services, money fund services, credit services, insurance services, and investment services.

[4] The synthesis of DIFI is divided into three steps: first, the logarithmic efficiency function is used to carry out dimensionless processing of the detailed index; second, objective weighting and subjective weighting are combined to determine the weight of indicators, that is, the weight of each specific index to the upper criterion layer is obtained by using the coefficient of variation method, and then the weight of each criterion layer index to the upper target is obtained by analytic hierarchy process (AHP); finally, according to the weight, the arithmetic average synthesis model is used to obtain the total value of DIFI.

where $D(\cdot)$is an indicative function. When the condition in parentheses is true, the value is 1; otherwise, it is 0. The symbol $\eta_m(m = 1, 2, \cdots, n)$ represents m threshold values, which can be estimated by the bootstrap method. The reason we choose this model is that if the factor of financial supervision is taken into account, the threshold regression can effectively reflect the inflection point phenomenon that may occur in the original linear relationship.

From the perspective of the external environment, financing constraints[5] are a major challenge for enterprises in the deployment of resources in addition to financial supervision. The stronger the financing constraints faced by enterprises, the more restricted their use of existing free funds; thus, the more difficult it will be to carry out high-quality green technology innovation. To explore the specific impact of financing constraints on the innovation-driven effect of DIF, we add financing constraints as the moderating factor into Eq. (1) and build a moderating effect model as in Eq. (3):

$$Y_{i,t} = \vartheta_1 + \vartheta_2 DIFI_{i,t} + \vartheta_3 FC_{i,t} * DIFI_{i,t} + \vartheta_4 FC_{i,t} + \sum \tau CV_{i,t} + \sum Year + \sum Prov + \lambda_i + \varepsilon \quad (3)$$

According to the calculation conclusion of Chinese enterprises by Ju et al. (2013), we select the absolute value of the enterprise's SA index as the proxy variable of financing constraints (FC). Notably, the data used to calculate the financial supervision variable come from the National Bureau of Statistics, and the SA index data are from the Guotai'an CSMAR database.

Results

Basic regression

Table 1 reports the basic regression results of Eq. (1), in which Columns (1) and (3) are the regression results without control variables while Columns (2) and (4) include the control variables. The results show that the influence coefficient of the development of DIF on the enthusiasm of enterprise green technology innovation is 0.108, which is significant at the 1% confidence level, and the influence coefficient on the quality of enterprise green technology innovation is 0.400, which is significant at the 5% confidence level. The development of DIF can significantly enhance the enthusiasm of enterprises for green technology innovation, which is specifically reflected in the growth of the application number of green patents. With the deepening of the development of DIF, the quality of green technology innovation in enterprises is also significantly improved, which is specifically reflected in the increased number of times the green patent is cited. Hypothesis H1a is supported.

From the coefficient comparison, we can also see that compared with the enthusiasm for green technology innovation, the development of DIF has a more far-reaching impact on the quality improvement of green technology innovation. The development of DIF can significantly improve the quantity and quality of corporate green technology innovation, and the effect of improving quality is higher than that of increasing quantity. Hypothesis H1b is supported. Therefore, the development of DIF can enhance the competitiveness of enterprises rather than floating on the surface. From the perspective of environmental protection, it also helps China and other developing countries achieve the goal of "carbon neutralization" at an early date and contributes to solving the world's energy and climate problems.

Table 1
Basic Regression Results.

	gre_pat		annu_citied	
	(1)	(2)	(3)	(4)
DIFI	0.109***	0.108***	0.415**	0.400**
	(0.04)	(0.04)	(0.17)	(0.16)
CV	-	Yes	-	Yes
Year, Prov	Yes	Yes	Yes	Yes
λ	Yes	Yes	Yes	Yes
_cons	-7.185	-62.126**	-103.048***	-234.790*
	(6.19)	(29.17)	(30.18)	(120.47)
adj. R^2	0.031	0.036	0.077	0.080
Observations	27088	27088	11111	11111

Notes: robust standard error is in parentheses; * represents p < 0.10, ** represents p < 0.05, *** represents p < 0.01; the following tables are the same.

The conclusion of this paper on the relationship between DIF and the number of enterprise green patent applications is basically consistent with existing research (Li et al., 2021; Wang et al., 2022; Xue et al., 2022); that is, the development of DIF can increase the number of green patent applications by enterprises. However, most studies use the number of green patent applications to measure the green technology innovation of enterprises in general and have not conducted in-depth discussion. We hold that only high-quality green patents can truly promote the progress of green technology, and the number of times a green patent is cited can only show the value of this technology. Therefore, this paper analyzes the number of green patent applications (to reflect the innovation enthusiasm of enterprises' green technology), provides a comparative analysis of the number of citations of green patents (to reflect the high-quality development of green technology in enterprises) and presents an in-depth discussion on the innovation-driven role of DIF.

The digital financial inclusion index released by Peking University can be divided into three dimensions: the breadth of coverage, the depth of use and the degree of digitization. The breadth of coverage is mainly measured by the number of effective third-party accounts; the depth of use is mainly measured by the use of digital financial services; and the degree of digitization is mainly measured by the user experience. To accurately describe the impact of digital inclusive financial development on enterprise green technology innovation, we conduct a regression analysis of the three subindicators in turn. The results are summarized in Table 2.

As seen from the results of Table 2, the three dimensions have a significant positive impact on the enthusiasm for green technology innovation of enterprises, which can bring benefits to enterprises from all aspects of the development of DIF. Its high degree of informatization and convenience creates a good environment for enterprises and stimulates their enthusiasm for transformation through green technology innovation. This is reflected in the positive growth in the number of green patent applications. From the point of view of the quality of enterprise green technology innovation, the coverage breadth and depth of DIF can significantly help enterprises carry out high-quality green technology innovation, while the degree of digitalization may not.

In the development of DIF, blindly pandering to the preferences of users and improving the convenience of online financial services regardless of the risk cost (such as excessively reducing small and microenterprises' online loan interest rates) is not the best way to improve the quality of green technology innovation. The comparison of coefficients shows that the breadth of coverage plays the most important role in promoting green technology innovation, followed by the depth of use. Therefore, only by expanding the group of users to DIF in an orderly manner, then improving services and functions on the basis of wide coverage, and finally constantly improving the

[5] According to Kaplan and Zingales (1997), the incompleteness of the market (such as information asymmetry and principal-agent problem) leads to the imbalance of internal and external financing costs, which is the so-called financing constraint. Following their ideas, Lamont et al. (2001) construct a multiway comprehensive index: KZ index, which avoids the defect of describing the corporate's financing situation from a single perspective. A similar index is the WW index Whited & Wu, 2006. To alleviate the endogenous problems in the construction of a financing constraint index, Hadlock and Pierce (2010) propose a classic measure of financing constraints that is based solely on the firm size and age, called the SA index.

Table 2
Basic Regression Results: Subdimension.

	gre_pat			annu_citied		
	(1)	(2)	(3)	(4)	(5)	(6)
DIFI_cb	0.117***			0.708***		
	(0.04)			(0.24)		
DIFI_ud		0.046**			0.155**	
		(0.02)			(0.08)	
DIFI_dl			0.029**			0.076
			(0.01)			(0.06)
CV	Yes	Yes	Yes	Yes	Yes	Yes
Year, Prov	Yes	Yes	Yes	Yes	Yes	Yes
λ	Yes	Yes	Yes	Yes	Yes	Yes
_cons	-62.758**	-57.650**	-53.356**	-263.856**	-217.929*	-205.080*
	(27.61)	(28.15)	(27.06)	(120.28)	(117.89)	(115.64)
adj. R^2	0.035	0.035	0.035	0.081	0.080	0.079
Observations	27088	27088	27088	11111	11111	11111

depth of individual use can we improve the innovation quality of green technology to the greatest extent. This further verifies the correctness of Hypotheses H1a and H1b.

Robustness test

This paper tests the robustness of the parameter estimation results of Table 1 in six ways, including changing the econometric model (Faleye et al., 2014; Moser & Voena, 2012), changing the statistical caliber of samples, refining the two types of dependent variables, considering the time-lag effect of independent variables, and supplementing the control variables (Chen et al., 2020). Full details can be seen in Appendix A.

Table B2 in Appendix B reports the regression results of the above robustness test, which shows that both the significance and the positive or negative sign of the coefficient are consistent with the previous conclusions, demonstrating the robustness of the basic regression results.

Endogeneity test

Although the development of DIF promotes the green technology innovation of enterprises to some extent, the green technology innovation of enterprises may also have a reverse effect on the development of DIF. To ensure the reliability of the research conclusions, the instrumental variable method is used to alleviate the endogeneity problems caused by reverse causality. In this paper, internet broadband penetration (Int_rate) is selected as the tool variable of the digital financial inclusion index (Wang & Song, 2022; Xie & Zhu, 2021). The data are compiled and calculated from the National Bureau of Statistics.

Table 3 shows the regression results obtained using the two-stage estimation method (2SLS). It can be seen from the table that there is a high correlation between tool variables and the digital inclusive financial index in the first stage, whether from a quantitative perspective or a qualitative perspective. In the second stage, the tests of the three major tool variables show that there are no problems of unidentifiable tool variables, weak tool variables and overidentification of tool variables, indicating the rationality of the selection of the tool variables. After the use of tool variables to alleviate endogeneity problems, the development of DIF still plays a significant role in the improvement of enterprise green technology innovation. The regression coefficient is higher than the basic regression, which again demonstrates the robustness of the research conclusion.

External environment test of green technology innovation

The development of DIF helps to increase the enthusiasm of Chinese enterprises for green technology innovation and helps to improve the quality of this innovation. In this process, will the change in the external environment of the enterprise have an impact on the existing mechanism? We attempt to analyze the constraints of the external environment on the innovation-driving effect of DIF from the perspectives of financial supervision and financing constraints.

The threshold effect of financial supervision

As we have emphasized, the essence of DIF is finance. The risk of the financial system will not disappear completely because of the introduction of new technology, but it will be more hidden and aggressive. Therefore, it is evident that financial supervision is very important. As a double-edged sword, only the appropriate intensity

Table 3
Endogeneity Test Results.

2SLS	First Stage DIFI	Second Stage gre_pat	First Stage DIFI	Second Stage annu_citied
IV: Int_ratio	-49.903***		-49.910***	
	(1.74)		(2.73)	
DIFI		0.986***		4.807***
		(0.19)		(1.03)
CV	Yes	Yes	Yes	Yes
Year, Prov	Yes	Yes	Yes	Yes
λ	Yes	Yes	Yes	Yes
K-P rk LM statistic	631.556		289.385	
K-P rk Wald F statistic	822.714		334.093	
Hansen J statistic	equation exactly identified		equation exactly identified	
N	27078		10975	

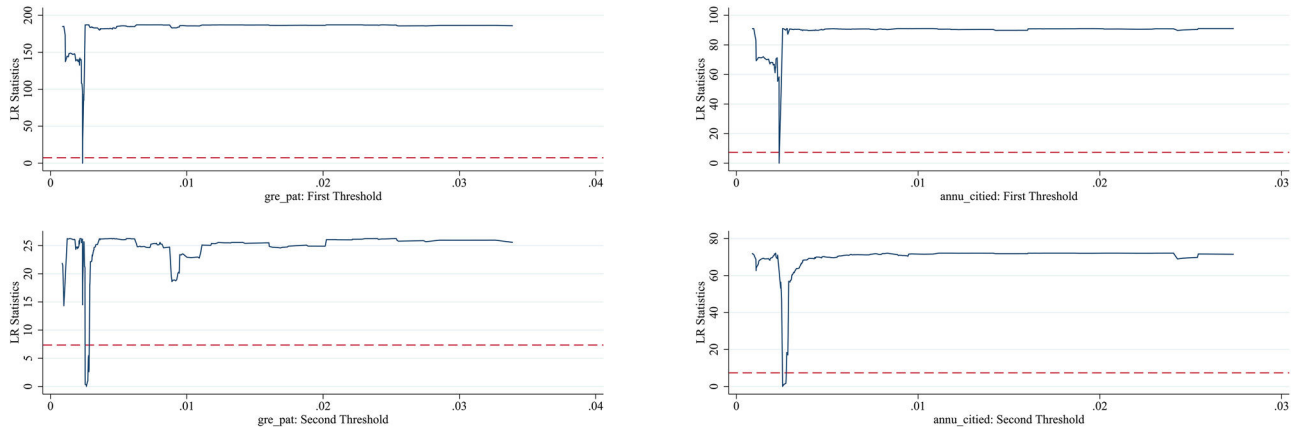

Fig. 3. Double Threshold Line Chart of Financial Supervision Intensity.

of financial supervision can balance the relationship between financial efficiency and financial security. How to effectively control financial risks while ensuring that DIF promotes the high-quality development of green technology innovation is the focus of this section.

According to Eq. (2), the number of thresholds was first tested by preliminarily setting n=3 and bootstrap=1000, and the corresponding results are shown in Table B3 in Appendix B. The threshold variable spvis of the independent variable does not pass the significance test in the triple threshold self-sampling test by the P value. However, the corresponding double threshold self-sampling test is significant at the 1% level, so the number of thresholds is finally determined as 2, and the self-sampling test (bootstrap=1000) is conducted again. The final results are shown in Fig. 3 and Table 4.

According to the principle of the threshold regression model, the threshold estimate is the corresponding value of the x-axis when the value of the y-axis (LR Statistics) approaches 0 in Fig. 3. The left side of Fig. 3 shows the likelihood ratio function diagram of the two threshold estimates (0.0024 and 0.0026) of the variable gre_pat under the 95% confidence interval. The right side shows the diagram of the 2 values (0.0024 and 0.0025) of the variable annu_citied. In the four subpictures, the lowest point of the LR statistics is obviously smaller than the critical value represented by the dotted line, so it can be concluded that the above threshold value is effective.

Table 4 presents the threshold estimates and the regression results of Eq. (2). It should be noted that for the inspection of the innovation quality, although the number of qualified samples under the condition of balanced panel data is small, the self-sampling times of bootstrap=1000 is large enough to compensate for the lack of accuracy.

Table 4
Threshold Effect Results of Financial Supervision Intensity.

Threshold value	Variable	gre_pat	annu_citied
θ_1=0.0024**θ_2=0.0026***	DIFI*D(spvis≤θ_1)	-0.012*	
		(0.007)	
	DIFI*D(θ_1<spvis≤θ_2)	0.030***	
		(0.008)	
	DIFI*D(spvis>θ_2)	-0.014**	
		(0.007)	
η_1=0.0024**η_2=0.0025***	DIFI*D(spvis≤η_1)		0.348***
			(0.124)
	DIFI*D(η_1<spvis≤η_2)		0.751***
			(0.140)
	DIFI*D(spvis>η_2)		0.360***
			(0.118)
Bootstrap=1000	CV	Yes	Yes
	_cons	-59.381***	-77.842
		(8.701)	(139.894)
	Observations	14340	1140

Different financial supervision intensity from the local government often makes the local development of DIF have a completely different impact on enterprises' innovation enthusiasm for green technology. When financial regulation is relatively loose (spvis≤0.0024), the marginal effect from the development of DIF on the enthusiasm for green technology innovation is -0.012, which is significant at the 10% confidence level. With the tightening of financial regulation (0.0024<spvis≤0.0026), the corresponding regression coefficient changes from negative to positive, that is, 0.030, and is significant at the 1% confidence level. When local financial regulation becomes more stringent (spvis>0.0026), the corresponding regression coefficient becomes negative again, that is, -0.014, which is significant at the 5% confidence level.

Thus, the intensity of government financial supervision has a significant policy orientation. If the regulation is relatively loose, the enterprise will have a high degree of freedom, so its attention will be attracted by businesses that more easily obtain benefits in the short term with the development of DIF rather than focusing on the R&D of green technology. Therefore, the number of green patent applications per unit time will decline. If the regulation is relatively strict, enterprises may face more regulatory constraints and a lack of motivation for green technology innovation, although the development of DIF brings financing convenience. Only by maintaining the appropriate intensity of financial supervision at all times can we ensure that with the development of DIF, enterprises will maintain enthusiasm for green technology innovation.

The development of DIF has a significant positive impact on the innovation quality of green technology under different intensities of financial supervision. When financial regulation is relatively loose (spvis≤0.0024), the value of the coefficient is 0.348; with the tightening of financial regulation (0.0024<spvis≤0.0025), the regression coefficient becomes 0.751; and when local financial regulation becomes more stringent (spvis>0.0025), the corresponding value becomes 0.360, all of which are significant at the 1% confidence level. Excessively loose or strict financial supervision will reduce financial efficiency. Hence, if the government adjusts the intensity of financial regulation, it will indeed to a sudden change in the innovation-driven mechanism of DIF. Hypothesis H2 is proven.

According to the above analysis, if a country wants its enterprises to maximize the dividends brought by the development of DIF in green technology R&D, then its central and local governments need to maintain a cautious attitude toward the regulatory intensity of the financial system, not only to maintain the risk bottom line of the financial system but also to ensure the innovation-driven effect of DIF as much as possible. Taking the relevant data of China as an example, this paper calculates the best intensity of provincial

financial supervision[6] to provide a reference for scholars to conduct relevant research in other countries. We believe that only financial supervision within a specific intensity can balance the efficiency and safety of regional financial development and inject power into the innovation of green technology of enterprises and the development of the national green economy.

The moderating effect of financing constraints

Against the background of the normal growth of DIF, to motivate enterprises to invest in the R&D of green technology, it is necessary to pay attention to the financing constraints of enterprises. This is also one of the important conditions for a country to successfully realize industrial transformation and upgrading. According to Eq. (3), variables FC and DIFI are composed into the interaction term to test the moderating effect of financing constraints. The results are summarized in Table 5. To avoid the influence of multicollinearity and make the marginal effects of coefficients consistent, the two variables constituting the interaction term have been centralized.

Table 5 shows the comparison between the regression results of Eqs. (1) and (3), in which Columns (2) and (4) show the moderating effect of financing constraints. The coefficients of the interaction term FC*DIFI are significantly negative at the 1% confidence level, which is opposite to the coefficient symbol in front of the core independent variable DIFI. When the development level of DIF is high, enterprises with smaller financing constraints will have greater enthusiasm to conduct research on green technology and promote their in-depth development, while enterprises with larger financing constraints will show a slight lack of motivation. For a stable enterprise, smaller financing constraints mean a more abundant financial environment, which can provide a more solid guarantee for its R&D on green technology.

The above research conclusions suggest that in China, state-owned enterprises and other large private enterprises have fewer financing constraints, and with the rapid development of DIF, they can provide substantial positive feedback on the central government's policy requirements for the development of the green economy. Of course, by the end of 2021, the number of small and medium-sized enterprises (SMEs) in China exceeded 48 million, accounting for almost 99% of the total number of enterprises as legal persons. Whether they can maintain high enthusiasm and patience for green technology innovation similar to large enterprises is an important factor that will affect the sustainable development of the green economy; otherwise, the phenomenon of "bad money driving out good" will occur. However, SMEs naturally have the characteristics of uncertain development, immature financial information disclosure and diseconomies of scale, which leads to their natural weakness in external financing. Therefore, in addition to the power of the market, it is necessary for the central and local governments to constantly improve the financing guarantee mechanism and information review mechanism and strive to create a good financing environment for SMEs. They should be provided with long-term policy support to solve the problem of difficult and expensive financing. Only in this way can as many enterprises as possible be willing and strong enough to promote the green upgrading and structural transformation of the industry, which can inject vitality into the healthy and sustainable development of the green economy.

Table 5
Moderating Effect Results of Financing Constraints.

	gre_pat		annu_citied	
	(1)	(2)	(3)	(4)
DIFI	0.108***	0.165***	0.400**	0.405**
	(0.04)	(0.05)	(0.16)	(0.16)
DIFI*FC		-0.219***		-0.630***
		(0.07)		(0.24)
FC		-72.389***		-259.385***
		(14.51)		(75.72)
CV	Yes	Yes	Yes	Yes
Year, Prov	Yes	Yes	Yes	Yes
λ	Yes	Yes	Yes	Yes
_cons	-62.126**	320.020***	-234.790*	1158.713***
	(29.17)	(66.75)	(120.47)	(237.45)
adj. R^2	0.036	0.081	0.080	0.154
Observations	27088	27088	11111	11111

[6] We believe that the best supervision intensity range for digital finance and financial technology in China should be between 0.0024 and 0.0025.

Enterprise characteristic test of green technology innovation

The development of DIF has a stable innovation driving effect on the green technology of enterprises. In this process, do the different characteristics of enterprises have an impact on the existing mechanism? We attempt to analyze the influence of enterprise characteristics on the effect of DIF from the point of view of the nature of property rights, the integration of general managers and chairmen, and the degree of industry pollution.

The nature of property rights

The most distinctive feature of China's economic system is the mutually beneficial coexistence of SOEs and non-state-owned enterprises (non-SOEs). Enterprises with different property rights have different resource endowments, incentive mechanisms and business objectives. SOEs are often in a monopoly position in the industry and have strong financial strength. They should not only pay attention to the growth of business performance but also need to be responsible for multiple objectives, such as social and environmental benefits. Therefore, SOEs also have certain political attributes. Green technology focuses on reducing the consumption of natural resources, reducing the damage to the ecological environment, and improving the efficiency of resource allocation, which includes the commitment of social responsibility. Therefore, the difference in property rights will inevitably make enterprises have different attitudes toward green technology innovation. Table 6 shows the differences in green technology innovation between SOEs and non-SOEs in the face of digital inclusive financial development.

In Table 6, when SOE=1, the enterprise is state-owned; when SOE=0, the enterprise is non-state-owned. The development of DIF plays a significant role in promoting the green technology innovation of SOEs, and it can significantly improve the quality of green technology innovation. In China, SOEs are an important force in promoting economic development. They have close ties with government

Table 6
Grouping Regression Results: Property Rights.

	gre_pat		annu_citied	
	SOE=1	SOE=0	SOE=1	SOE=0
DIFI	0.310***	-0.004	0.855***	-0.156
	(0.09)	(0.02)	(0.26)	(0.14)
CV	Yes	Yes	Yes	Yes
Year, Prov	Yes	Yes	Yes	Yes
λ	Yes	Yes	Yes	Yes
_cons	-255.820**	-0.827	-580.832*	-10.228
	(106.73)	(7.63)	(300.50)	(43.71)
adj. R^2	0.069	0.036	0.105	0.067
Observations	9453	17635	4293	6818

departments and are more likely to obtain support from the outside world (such as loose financing and regulatory environment) so that they can make full use of the achievements of DIF development and apply them to the R&D of green technologies. Second, state-owned enterprises, as leaders of various industries, need to actively respond to the national policy call to develop a green economy. They assume more responsibility for reducing energy consumption and carbon emissions and promoting sustainable economic development, so they have always held a positive attitude toward green technology innovation. Therefore, the development of DIF has brought them new technical support, and the quality of green technology innovation has been greatly improved. In contrast, non-SOEs lack motivation, and the development of DIF will not significantly encourage them to pay more attention to green technology innovation.

The phenomenon of CEO duality

CEO duality is the situation in which a chief executive officer (CEO) also holds the position of the chairman of the board. In the framework of principal-agent theory, there is no final conclusion on CEO duality. This situation may increase the CEO's control over the company, weaken the independence and supervisory function of the board of directors (Bansal & Thenmozhi, 2021), and virtually increase the external audit cost (Gul & Tsui, 2001). At the same time, the vague boundaries of power levels are not conducive to communication and cooperation between concurrent holders and other executives of the company, reducing management efficiency (Anderson & Brown, 2010). However, some scholars believe that CEO duality can give a CEO unified decision-making power (Liu et al., 2020; Tang, 2017), which can help enterprises grasp opportunities in time or realize transformation smoothly, thus helping the company form strategic thinking (Donaldson & Davis, 1991). Therefore, whether there is CEO duality also affects enterprises' views on the development of green technology. Table 7 shows the differences in green technology innovation among different types of enterprises in the face of the development of DIF.

In Table 7, duality=1 indicates the existence of CEO duality in the enterprise; duality=0 indicates that there is no such situation in the enterprise. The development of DIF plays a significant role in driving innovation for enterprises without CEO duality, especially because it can significantly improve the quality of green innovation. On the other hand, enterprises with CEO duality are not enthusiastic about it, which means that the development of DIF will not make them pay more attention to green technology. The expansion of power brought about by duality makes CEOs have more room for rent-seeking. This selfish motivation weakens not only the long-term development strategy of enterprises but also their sense of social responsibility. Compared with green technology innovation, enterprises with CEO duality may pay more attention to short-term interests. Therefore, improving the corporate governance structure, especially ensuring the separation of the power of management and supervision, is an important condition to ensure that the development of DIF continues to drive the high-quality innovation of green technology.

The degree of industry pollution

We divide the pollution-intensive industries (PIIs), including thermal power, iron and steel, cement, electrolytic aluminum, coal, metallurgy, building materials, mining, chemical, petrochemical, pharmaceutical, brewing, papermaking, fermentation, textile and tanning, with reference to document No. 373 of 2008 published by the Ministry of Ecology and Environment of China. The reason for choosing PIIs as the object of study is that according to document No. 24 of 2021 published by the Ministry of Ecology and Environment of China, listed companies belonging to PIIs must disclose their annual environmental report, which includes the enterprise's environmental management information and carbon emissions, while listed companies in non-PIIs are encouraged to disclose it. Table 8 shows the differences in green technology innovation among different types of enterprises in the face of the development of DIF.

In Table 8, when PII=1, the enterprise belongs to industries with heavy pollution; when PII=0, the enterprise does not belong to them. The development of DIF cannot enhance the enthusiasm of PIIs for green technology innovation. A possible reason is that enterprises belonging to PIIs are basically resource-intensive or capital-intensive, and their daily operation depends on a large amount of professional technology and equipment. Therefore, the return on investment is slow but deterministic, while the high cost of green technology R&D undoubtedly brings a burden to the daily production of such enterprises and the unknown income reduces investment interest (Orsato, 2006). In fact, if the environmental pollution penalty faced by enterprises is relatively low, the power of government regulation (including local government regulation and central vertical regulation) must be used to force PIIs to improve their attention to green technology (Han, 2020; Leiter et al., 2011). Therefore, the nonmandatory convenience brought by the development of DIF makes it difficult to raise these enterprises' attention to green technology. When government regulators intervene, the development of DIF can significantly improve the innovation quality of heavily polluting enterprises in green technology. In addition, for non-PII enterprises, the development of DIF can significantly improve their enthusiasm for green technology innovation. However, whether it can effectively promote its high-quality development requires further testing.

Conclusions, policy implications and research prospects

Main conclusions

Innovation is a process in which entrepreneurs combine factors of production and establish a new production function (Schumpeter, 1934). Against the background of the globalization of environmental governance, the "green" attribute of technological progress has

Table 7
Grouping Regression Results: Phenomenon of Two-in-One.

	gre_pat		annu_citied	
	Duality=1	Duality =0	Duality =1	Duality =0
DIFI	-0.036	0.141***	-0.258	0.475***
	(0.06)	(0.05)	(0.26)	(0.17)
CV	Yes	Yes	Yes	Yes
Year, Prov	Yes	Yes	Yes	Yes
λ	Yes	Yes	Yes	Yes
_cons	10.649	-96.213**	1.395	-336.938*
	(21.26)	(41.35)	(91.53)	(180.32)
adj. R^2	0.025	0.045	0.094	0.084
Observations	7683	19089	2968	7993

Table 8
Grouping Regression Results: Industry Pollution Degree.

	gre_pat		annu_citied	
	PII=1	PII=0	PII=1	PII=0
DIFI	-0.011	0.148***	0.382*	0.315
	(0.05)	(0.06)	(0.23)	(0.23)
CV	Yes	Yes	Yes	Yes
Year, Prov	Yes	Yes	Yes	Yes
λ	Yes	Yes	Yes	Yes
_cons	-1.901	-82.025**	-131.121	-234.510
	(6.77)	(40.10)	(84.29)	(153.84)
adj. R^2	0.015	0.044	0.035	0.103
Observations	8675	18413	3336	7775

received increasing attention from many countries. Because this attribute involves the efficient use of resources and friendliness to the social environment, the continuous progress of green technology is not only an important condition to promote the high-quality development of the global green economy but also an important means to solve the problem of global warming. At the same time, the rapid development of the digital economy has promoted the deep integration of inclusive finance and fintech. Digital inclusive finance (DIF) provides convenient financial services to an increasing number of individuals. The role it plays in the high-quality development of the green economy, however, remains an open question that many scholars have discussed from many angles.

This paper contributes to answering this question from the perspective of green technology innovation. We select Chinese A-share listed companies from 2011 to 2020 as the research object and match their green technology innovation data with the DIF index released by Peking University to build a special database. We find that the comprehensive development of DIF (including the breadth of coverage, the depth of use and the degree of digitization) can improve the enthusiasm of enterprises for the R&D of green technology. However, in the process of the development of DIF, catering excessively to the needs and preferences of users and improving the convenience of online financial services regardless of risk cost (that is, improving the degree of digitization) is not the best way to improve the quality of green technology innovation. Only by expanding the group of users to DIF in an orderly manner, then improving services and functions on the basis of wide coverage, and finally constantly improving the depth of individual use can we improve the innovation quality of green technology to the greatest extent.

In the analysis of the external environment of enterprises, two key findings emerge. First, financing constraints have an inhibitory effect on the innovation-driven effect of DIF. Since small and medium-sized enterprises (SMEs) have natural weaknesses in external financing, it is necessary for governments to provide them with long-term policy support to solve the problem of "difficult and expensive financing" instead of the market. Second, the innovation-driven effect of DIF is affected by the intensity of financial supervision. Through the construction of regional financial supervision intensity indicators, we find that when financial regulation is too loose or too strict, the development of DIF will restrain enterprises' enthusiasm for green technology innovation; at the same time, the corresponding innovation quality improvement is small, which means damage to financial efficiency. Based on the calculations, this paper presents the ideal range of financial supervision intensity of various provinces in China as a reference for other countries.

In the analysis of the internal characteristics of enterprises, three key findings emerge. First, the development of DIF can significantly promote the green technology innovation of state-owned enterprises (SOEs) in China due to their status and social responsibility. Second, the development of DIF cannot significantly promote the green technology innovation of enterprises in the situation of CEO duality, which means that the separation of the power of management and supervision in a company is of great importance because of the possibility of rent-seeking and lack of social responsibility. Third, no matter what the development of DIF is, as long as the potential punishment for environmental pollution is less than the cost of green technology R&D, there will be no enthusiasm among enterprises belonging to pollution-intensive industries (PIIs) for green technology innovation. Therefore, the industrial upgrading of such enterprises requires the supervision and encouragement of government departments.

Policy implications

The development of DIF can enhance the core competitiveness of the green technology innovation of enterprises while promoting the green transformation and upgrading of enterprises to help China and other countries achieve the goal of carbon neutralization at an early date. This will contribute to solving global energy and climate problems.

Government agencies of developing countries, including China, should continue to promote the construction of the DIF system, utilize the advantages of big data and artificial intelligence technology in solving the mismatch of traditional financial resources, and guide the flow of financial resources to a green and low-carbon economy, which is of great significance for developing countries to achieve healthy economic development. In addition, for SMEs that are on the weak side of external financing, the government should continuously improve and strengthen the financing function and pricing power of the capital market to strengthen the innovation-driven effect of DIF on green technology. For large SOEs on the strong side of external financing, government regulatory departments should adjust the intensity of financial supervision in accordance with local conditions cautiously and flexibly, not only preventing the accumulation of credit risks caused by excessive and disorderly financing but also creating a loose and orderly policy environment for corporate green technology innovation.

For financial institutions, a multidimensional organization framework of DIF should be built that utilizes the influence of large financial institutions in resource allocation and the flexibility of small and medium-sized financial institutions so they can complement each other's strengths and continue to expand the coverage of DIF. On this basis, financial institutions can continuously strengthen the application of financial science and technology methods, providing personalized financial products and services for enterprises. Specifically, they should also improve the digital risk control system for the credit evaluation of SMEs and standardize the service management process of DIF. Only in this way can they cultivate user stickiness on the basis of wide coverage and gradually improve the degree of digitization under the conditions of perfect supervision and mature technology.

Research limitations and prospects

Given the limitations of the length of the paper and the time and energy of the authors, the research deficiencies of this paper are as follows. (1) There are deficiencies in the data sample used in the study. The research sample of this paper is from China; however, the development of DIF and its impact on green technology innovation are global. Furthermore, the time range of the data sample is from 2011 to 2020. Since the application for the use of provincial DIFI data in 2021 has not been approved, this paper does not analyze the green technology innovation of enterprises since 2021. Therefore, the research sample of this paper is relatively small. (2) The research theme needs to be improved. This paper only studies the impact of DIF on corporate green technology innovation; however, its influence on other aspects (e.g., enterprise operation and management, growth of the green economy) is also worthy of attention. (3) The heterogeneity analysis is not deep enough. This paper only analyzes the heterogeneity of the research theme from the internal characteristics of the company and lacks a macro perspective.

We will improve upon the defects of this article with regard to data and research in follow-up research. For the topics discussed in this paper, we can conduct predictable research from the following aspects: (1) the great impact of the digital development of inclusive finance will not only promote the innovation of green technology but also have a substitution effect on the human capital of enterprises, which is worthy of attention; (2) the development of the digital economy led by DIF will also have an agglomeration effect on the manufacturing industry, and the resulting environmental pollution control issues are closely related to the development of the digital economy. Against this background, the behavior of the government is particularly important, and further research is urgently needed; (3)

in addition to promoting macroeconomic growth and the transformation and upgrading of enterprises, whether the development of DIF will have an impact on individual investment decisions and consumption behaviors is worth discussing.

Funding

We acknowledge financial support from Key Projects of the National Social Science Fund of China (22AZD095)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

A.1. Replace the Regression Model

Because the patent quantity data and cited times data of A-share listed companies have a large number of zero accumulations on the left, which indicates the characteristics of truncated data, we use the Tobit model to retest the basic model Eq. (1) (Faleye et al., 2014). In addition, we put the interaction term of the year and province (Year*-Prov) into the new model to improve the control of endogeneity by using the approach of the high-order joint fixed effect (Moser & Voena, 2012).

A.2. Change the Statistical Caliber of Independent Variables

Considering the huge development differences among Chinese cities, it may be difficult for data at the provincial level to fully show the inherent logic of DIF and enterprise green technology innovation. Therefore, we change the statistical caliber of the core independent variable. The Peking University Digital Financial Inclusion Index at the city level is used to match the sample again to measure the impact on enterprise green technology innovation.

A.3. Rethinking Innovation Enthusiasm

In China, green patents of enterprises include “patents of green inventions” and “patents of the green utility model”. According to the relevant definition of the Patent Law of the People’s Republic of China, the former is the creation of products and methods with outstanding substantive characteristics and remarkable progress; the latter involves the improvement of tangible products and pays attention to practical value, and the level of creativity is lower than the former. With regard to the difference between the two, green utility model patents are closely related to the daily production and operation of enterprises; regardless of whether DIF develops, enterprises always have the motivation to conduct research and application. It cannot truly reflect the impact of digital inclusive financial development on the enthusiasm for green technology innovation. Therefore, the application number of green utility model patents from the original variable is removed, and the variable named gre_inv is taken as the new dependent variable, which indicates the application number of green invention patents.

A.4. Rethinking Innovation Quality

If an enterprise develops either a green invention patent or a green utility model patent only for its own needs, the cited times of the patent may mainly come from self-citation and contribute little to the development of the industry and society. Admittedly, the birth of each green patent comes from the needs of the enterprise itself, but if self-citations are excluded, the number of citations is still very high, which can show that the green patent has high value. Therefore, to strive for objectivity of the quality perspective, the self-citation times of the original variable annu_citied are removed, and the variable annu_citied2 is taken as the new dependent variable.

A.5. Consider the Growth of Enterprises

The growth of enterprises means an increase in profitability and the expansion of scale, which will often promote their own level of green technology innovation (Chen et al., 2020). If the growth factor of an enterprise is not considered, the effect of the development of DIF will be overestimated, so we choose the annual growth rate of operating income as the proxy variable (growth) to measure the growth factor of the enterprise and put it into the queue of existing control variables.

A.6. Consider the Time-Lag Effect

The impact of the development of DIF on the green innovation of enterprises is not immediately reflected in the number of green patents applied and citation times, in which there is a time-lag effect. In addition, there is a time-lag effect from the application of the green patent to the citation. In the analysis of innovation enthusiasm, this paper addresses the DIF index lagging one period and the DIF index lagging two periods in the analysis of innovation quality.

Appendix B

Table B1
Descriptive Statistics.

Variables	N	Mean	σ	Min	Max
gre_pat	27088	8.16	46.42	0.00	1612.00
annu_citied	11111	18.55	89.71	0.00	2455.00
DIFI	27088	256.78	99.62	16.22	431.93
DIFI_cb	27088	237.42	96.86	1.96	397.00
DIFI_ud	27088	261.99	104.86	6.76	488.68
DIFI_dl	27088	311.24	116.85	7.58	462.23
age	27088	2.80	0.37	0.00	4.13
tobinq	27088	2.02	1.35	0.86	9.82
roa	27088	0.04	0.07	-0.36	0.27
lev	27088	0.42	0.21	0.05	0.96
cashflow	27088	0.09	0.19	-0.82	0.69
SOE	27088	0.35	0.48	0.00	1.00
top1	27088	34.59	15.00	0.29	89.99
indratio	27088	0.38	0.07	0.17	0.80
opin	27088	0.03	0.17	0.00	1.00

Table B2
Regression Results of Robustness Test.

Tobit	gre_inv		annu_citied2	
	(1)	(2)	(3)	(4)
L1.DIFI_city	0.177***	0.205***		
	(0.03)	(0.03)		
L2.DIFI_city			0.347***	0.352***
			(0.10)	(0.10)
CV	Yes	Yes	Yes	Yes
Year, Prov	Yes	-	Yes	-
Year*Prov	-	Yes	-	Yes
λ	Yes	Yes	Yes	Yes
_cons	-49.025***	-46.966***	-32.991*	-48.490**
	(6.77)	(7.75)	(19.86)	(23.66)
Observations	21554	21554	6721	6721

Table B3
Self-Sampling Results of Threshold Effect.

Dependent variable	Threshold variable	Threshold number	F-stat	Prob
gre_pat	spvis	Single	45.66	0.0220
		Double	164.11	0.0000
		Triple	9.07	0.8080
annu_citied	spvis	Single	24.78	0.0580
		Double	72.96	0.0020
		Triple	4.24	0.8640

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