Article

The Incentive Effect of Digital Finance on Innovation of Small- and Medium-Sized Enterprises Considering Heterogeneity: An Empirical Study Based on Chinese-Listed Firms

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Abstract: The development of digital finance provides new opportunities for solving the dilemma of innovation financing for small- and medium-sized enterprises (SMEs). This study empirically examined the heterogeneous characteristics and mediating mechanisms of digital finance and its incentive effects on SME innovation using panel data of Chinese and GEM board-listed companies from 2010 to 2021. It was found that digital finance can significantly incentivize SME innovation; however, there are differences in efficacy among digital finance sub-dimensions, with breadth of coverage having the strongest effect, followed by depth of use, and digitization degree having a non-significant effect. Meanwhile, there is heterogeneity in the incentive effect of digital finance on SME innovation, which is manifested as private SMEs and SMEs in regions with stronger financial regulations and a higher degree of marketization being more likely to be incentivized by digital finance to innovate. In addition, digital finance can indirectly incentivize SMEs to innovate through three paths: alleviating financing constraints, improving risk tolerance, and solving information asymmetry.

Keywords: digital finance; SMEs; innovation; heterogeneity

1. Introduction

Innovation is the core driving force of China's high-quality economic development, and the key to successful innovation is microenterprises being willing to develop independent innovation. Small- and medium-sized enterprises (SMEs) are among the main players in innovation and are also the most promising and active innovators. Practice shows that major breakthrough innovations usually originate from SMEs rather than large enterprises. According to statistics from the China Intellectual Property Office, by 2023, the proportion of effective invention patents owned by Chinese enterprises reached 71.2%, of which science and technology SMEs accounted for about three-quarters of the total number, at 73.4%. Therefore, incentivizing SMEs to innovate and fostering their independent innovation capability are driving the development of China's real economy.

In practical terms, a continuous and sufficient supply of financial resources is necessary to guarantee the stable development of innovation among SMEs. However, SMEs face numerous financial challenges in the process of innovation. Firstly, financing channels are limited, as traditional banks impose strict loan approval criteria for SMEs, and those lacking collateral or a solid credit history often struggle to secure loans. Secondly, the cost of financing is high; even when funds are obtained, SMEs frequently encounter elevated interest rates and fees, increasing the financial pressure. Additionally, there is the significant issue of information asymmetry, which makes it difficult for financial institutions to accurately assess the innovation potential of SMEs, thereby undermining investor confidence. Lastly, the long innovation cycle and slow capital returns further strain SMEs' liquidity, exacerbating their financing difficulties.

With the rapid development of digital technologies, the deep integration of traditional finance and digital technology has given rise to digital finance as an emerging business model. In the current economic environment, it is both critical and urgent that digital finance support SME innovation. Digital finance, through technologies such as big data, artificial intelligence, and blockchain, helps address issues such as the information asymmetry and high financing costs inherent in traditional financial systems, enabling SMEs to access funding more conveniently and accelerate their innovation processes [1]. At the same time, digital finance lowers financing thresholds and costs, enhancing the efficiency of capital allocation, which is a critical factor, particularly in the early stages of SME innovation [2]. More importantly, the widespread application of digital finance can promote innovation and entrepreneurship, drive industrial transformation and upgrading, and thus enhance the vitality of the urban economy [3]. Against the backdrop of increasing global economic uncertainty, digital finance has become an inevitable choice for incentivizing SME innovation and achieving high-quality economic development. However, the specific incentive effects of digital finance have not yet been quantified. Do these incentives exhibit heterogeneous characteristics? What are the mechanisms at work? These questions warrant further investigation.

Based on this, in this study, we took listed companies on China's Growth Enterprise Market (GEM) and SME boards as the research objects to examine the incentive effects of digital finance on SME innovation. We discuss the heterogeneous characteristics across three dimensions: ownership structure, financial regulation, and the degree of marketization. Additionally, we focused on analyzing the incentive mechanisms from the perspectives of financing constraints, information asymmetry, and risk tolerance. The research findings are intended to provide policy recommendations for SMEs to leverage digital finance to achieve innovative development.

2. Review of the Literature and Research Hypotheses

Digital finance, as an emerging financial service model, has profoundly transformed the functioning of the global financial system and has had a significant impact on society and the economy. The existing literature primarily explores the development and effects of digital finance from the following perspectives.

The first is digital finance and the income gap. Hu et al. [4] utilized three waves of data from the China Household Panel Study and the Digital Financial Inclusion Index to examine the relationship between digital finance and household income inequality. The study revealed a Kuznets curve effect of digital finance on both the Theil index and the Gini coefficient, suggesting that while digital finance may initially increase inequality, it ultimately contributes to reducing household income inequality in the long term, thus adding valuable insights to the existing body of research. Das and Chatterjee [5] investigated the direct and indirect effects of ICT expansion through digital financial channels on poverty and income inequality at the local level in India. The study found that while ICT had no direct effect on income inequality, financial inclusion positively influenced both urban and rural inequality. However, the expansion of ICT within the banking sector diminished the positive effect of financial inclusion on urban inequality while leaving rural inequality unaffected.

The second is digital finance and entrepreneurship. Wu and Wu [6] selected data from the 2017, 2019, and 2021 China Household Finance Surveys as a research sample. In that study, they found that digital inclusive finance can promote household entrepreneurial decisions through two mechanisms: fostering innovation behavior and alleviating financing constraints. Liu et al. [7] utilized data from the 2018 China Migrant Population Dynamic Survey and the Digital Financial Inclusion Index to conduct an empirical analysis. The results indicate that local digital financial development is positively correlated with both the likelihood of entrepreneurship and the quality of entrepreneurial ventures. From the perspective of entrepreneurial motivation, digital finance significantly influences immi-

grants' entrepreneurial decisions, enhancing not only necessity-driven entrepreneurship but also opportunity-based entrepreneurial initiatives.

The final perspective is digital finance and consumption. Song et al. [8] using data from the China Household Finance Survey, assess the impact of digital inclusive finance on household consumption volatility. The findings reveal that digital inclusive finance significantly reduces these fluctuations. Mechanism tests suggest that the primary channels for this effect are through promoting entrepreneurship and reducing income volatility. Furthermore, heterogeneity analysis shows that the smoothing effect of digital inclusive finance on household consumption volatility is more pronounced among households with strong financial standing, higher financial literacy, and access to the Internet, particularly in rural areas. Yang et al. [9] examined the impact of digital inclusive finance on the survival consumption of rural households in China and found that rural residents in regions with more developed digital inclusive finance tend to have higher levels of survival consumption.

In summary, existing research has extensively discussed topics such as income inequality, entrepreneurship, and consumption. However, there remains a clear gap in the research on the relationship between digital finance and SME innovation, particularly regarding the effectiveness, heterogeneous characteristics, and transmission mechanisms of digital finance in enabling SME innovation. These aspects remain unclear and require further investigation. Therefore, this study makes an important contribution to the field.

2.1. The Impact of Digital Finance on SME Innovation

Scholars have conducted a series of studies on the relationship between digital finance and technological innovation. Chen et al. [10] studied the impact of digital finance on green technological innovation in the Chinese manufacturing industry and found that digital finance directly promotes green innovation and helps enterprises overcome financing constraints by providing alternative sources of funding. Zhu et al. [11] found that digital finance positively affects the innovation performance of Chinese manufacturing firms and that financial constraints are a potential channel for the operation of digital finance. Lin and Zhang [12], utilizing a panel of data from 31 provinces in China during the period 2011–2020, empirically found that digital finance significantly affects renewable energy technological innovation. Razzaq et al. [13] found that digital finance plays a pivotal role in driving innovation in renewable energy technology, with government intervention further enhancing its marginal effects. Studies have paid more attention to the impact of digital finance on different types of innovation outputs and less to the key issue of the innovation financing constraints of SMEs.

In reality, digital finance offers various financing channels, such as crowdfunding, P2P lending, and online loans. These platforms enable SMEs to more easily access financial support, thereby facilitating the implementation of innovative projects. Additionally, digital financial services reduce transaction costs and operational expenses through online platforms and automated processes, allowing SMEs to invest in innovation at a lower cost. Moreover, digital finance platforms typically provide rich data analytics tools, helping SMEs better understand market demand and customer behavior, thereby driving data-driven innovation [14]. Therefore, this paper proposes the following hypothesis:

Hypothesis 1. *Digital finance can directly incentivize SME innovation.*

2.2. Heterogeneous Characteristics of Digital Finance's Impact on SME Innovation

It is well known that the ownership structure of SMEs varies, and the intensity of financial regulation and the degree of marketization also differ across regions in China. As a result, the impact of digital finance on SME innovation exhibits certain heterogeneity. Firstly, compared to state-owned SMEs with government guarantees, private SMEs face higher loan thresholds and capital costs and often suffer from "ownership discrimination" in innovation financing. Therefore, digital finance has a more pronounced incentive effect on the innovation activities of private SMEs. Secondly, considering the risks associated with

digital finance, such as data breaches and financial fraud, effective financial regulation is essential to fully leverage the advantages [15]. Clearly, higher financial regulatory intensity in a region facilitates the standardized development of digital finance, thereby better supporting innovation financing for SMEs. Finally, a higher degree of marketization implies a more developed and diversified financial market, allowing SMEs to more easily access financing through digital finance channels, which in turn promotes the implementation of SME innovation projects. Therefore, this paper proposes the following hypotheses:

Hypothesis 2. *Compared to state-owned SMEs, digital finance has a stronger incentive effect on innovation among private SMEs.*

Hypothesis 3. *In regions with strong financial regulation, digital finance has a more pronounced incentive effect among innovation in SMEs.*

Hypothesis 4. *In regions with a higher degree of marketization, digital finance has a stronger incentive effect among innovation in SMEs.*

2.3. Mechanisms of Digital Finance's Impact on SME Innovation

Digital finance can indirectly drive SME innovation through various mechanisms. Firstly, digital finance rapidly responds to the funding needs of SMEs and leverages credit evaluation systems to quickly extract basic information and credit data. This enables a quick assessment of their operational conditions and financial credibility, effectively alleviating their financing constraints. Secondly, digital finance enhances the flexibility of capital acquisition for SMEs, reducing the likelihood of forgoing positive net present value projects. This increases their capacity to cope with external shocks and uncertainties while also reducing the probability of financial difficulties, thereby raising their risk tolerance [16]. Lastly, digital finance effectively mitigates information asymmetry through technologies such as big data, artificial intelligence, and blockchain. These technologies enable the collection, processing, and analysis of vast amounts of user data, providing more transparent information and allowing financial institutions to more accurately assess users' credit risk. Additionally, smart contracts and distributed ledger technology enhance the transparency and security of transactions, reducing information asymmetry and reducing the likelihood of moral hazards and adverse selection, thereby incentivizing innovation in SMEs [17]. Therefore, this paper proposes the following hypotheses:

Hypothesis 5. *Digital finance incentivizes SME innovation by alleviating financing constraints.*

Hypothesis 6. *Digital finance incentivizes SME innovation by increasing the level of risk tolerance.*

Hypothesis 7. *Digital finance incentivizes SME innovation by reducing information asymmetry.*

Based on the above theoretical mechanisms and research hypotheses, we set the following research framework, as shown in Figure 1. Next, we carried out empirical tests according to the research framework.
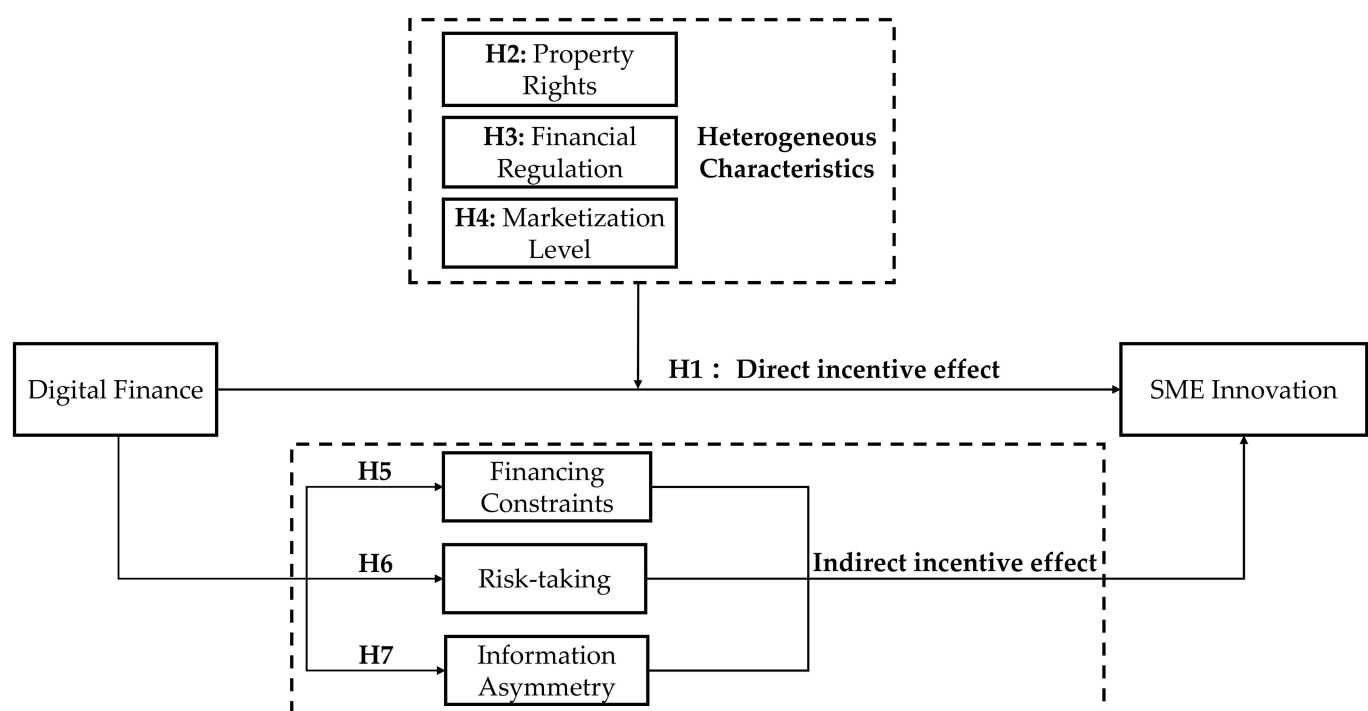
Figure 1. Theoretical framework.

3. Methodology and Data

3.1. Econometric Model

Hypotheses H1–H4 were tested according to the research framework, and in order to avoid the influence of other variables on the estimation results, 8 control variables were used in this study. The specific baseline model is as follows:

$$\ln Pat_{ijt} = \alpha_0 + \alpha_1 DIF_{jt} + \alpha_2 \sum Controls_{ijt} + \sum ind + \sum year + \varepsilon_{ijt} \tag{1}$$

where here i denotes firm, j denotes city, and t denotes year; is the explanatory variable, which denotes the innovation capacity of SMEs; is the core explanatory variable, which denotes the level of digital finance at the city level, including three sub-dimensions (coverage breath (DIF_CB), depth of use (DIF_U), and digitization level (DIF_DL)); $\sum Controls$ denotes the series of control variables, which specifically include firm size (*Size*), firm age (*Age*), liability on asset ratio (*Lev*), return on assets (*Roa*), fixed assets (*Fix*), duality (*Dual*), the share of independent directors (*Inde*), and ownership concentration (*Top*); ε denotes random perturbation terms; $\sum ind$ denotes industry dummy variables; and $\sum year$ denotes year dummy variables.

In order to test research hypotheses H5–H7, based on the baseline model (1), we set up the following mediated effects model:

$$D_{ijt} = \beta_0 + \beta_1 DIF_{jt} + \beta_2 \sum Controls_{ijt} + \sum ind + \sum year + \varepsilon_{ijt} \tag{2}$$

$$\ln Pat_{ijt} = \theta_0 + \theta_1 DIF_{jt} + \theta_2 D_{ijt} + \theta_3 \sum Controls_{ijt} + \sum ind + \sum year + \varepsilon_{ijt} \tag{3}$$

where D denotes the mediating variables, including financing constraints (*KZ*), risk tolerance (*Zsco*), and information asymmetry (*Asym*). The remaining variables are explained in the baseline model (1). According to Baron and Kenny [18], if $\alpha_1, \beta_1,$ *and* θ_2 are significant and θ_1 is significant but less than α_1, it means that there is a partial mediation effect; if $\alpha_1, \beta_1,$ *and* θ_2 are significant and θ_1 is insignificant, it means that there is a full mediation effect.

3.2. Variable Selection

3.2.1. Explained Variables: SME Innovation (lnPat)

SME innovation is a dynamic economic activity involving knowledge internalization, technology development, and product marketization. Scholars have selected different proxies to represent SME innovation, including R&D investment [19,20] and a number of patent applications (grants) [21]. Patents are the direct product of SMEs' innovation, with attributes of innovation knowledge accumulation and invention creation. Therefore, in this study, we used the number of patent applications to measure SME innovation. We also adopted R&D intensity and the number of patent applications in each category as replacement indicators for robustness testing.

3.2.2. Explanatory Variable: Digital Finance (DIF)

Scholars mainly measure the level of China's digital finance development from two perspectives, using the digital finance keyword search index [22] and the Peking University Digital Inclusive Finance Index [23,24]. Considering that digital finance keywords are updated and iterated over time, the timeliness of the keyword search index is poor and the accuracy is low. Therefore, in this study, we chose the Peking University Digital Inclusive Finance Index as a proxy index for digital finance. This index was compiled by Peking University and Hangzhou Ant Gold Service Financial Services Co. using Alipay transaction data; involved three sub-indicators: breadth of coverage, depth of use, and degree of digitization; and covered the level of digital finance development in 31 provincial-level regions, 337 prefectural-level regions, and more than 2800 county-level regions in China [25].

3.2.3. Mediation Variables

The mediation variables in this study include financing constraints, risk tolerance, and information asymmetry.

Financing constraints (*KZ*): In general, indicators such as net operating cash flow, debt level, cash holdings, and corporate growth can indirectly reflect corporate financing constraints [26]. With the depth of research, scholars have adopted various methods to measure corporate financing constraints, such as through the KZ index, WW index, SA index, and FC index. For this reason, referring to Hadlock and Pierce [27], this study adopted the KZ index to measure SME financing constraints. A larger KZ index indicates stronger financing constraints.

Risk tolerance (*Zsco*): This is a commonly used indicator to measure risk tolerance and mainly includes earnings volatility, stock return volatility, and debt ratio [28]. In this study, the Zscore score of financial risk was used to indicate the financial risk tolerance of SMEs. When the Zscore is larger, it means that the probability of SMEs falling into financial risk is smaller and their risk tolerance is higher; a lower score means lower risk tolerance.

Information asymmetry (*Asym*): Analysts are the intermediaries of information transfer between enterprises and investors, often through internal and external channels, to collect corporate information to study the earnings trends and investment values and provide a reference for investors; therefore, analysts are concerned about the information environment that can affect the market [29]. Analyst attention was used to measure the information asymmetry of SMEs. Higher Asym indicates more symmetry; lower Asym indicates asymmetry.

3.2.4. Control Variables

According to the related research on the factors influencing SME innovation [30], this study controls other variables affecting SME innovation as follows: (1) Firm size (*Size*), expressed as the natural logarithm of the total assets of the enterprise; (2) Firm age (*Age*), expressed as the number of years of the enterprise's establishment; (3) Liability on asset ratio (*Lev*), expressed as total liabilities/total assets; (4) Return on assets (*Roa*), expressed as net profit/total assets; (5) Fixed assets (*Fix*): expressed as net fixed assets/total assets;

(6) Duality (*Dual*), for which the position of chairman and general manager together is taken as 1, otherwise 0; (7) Share of independent directors (*Inde*), expressed as the percentage of independent directors to the total number of directors; (8) Ownership concentration (*Top*), expressed as the proportion of shares of the largest shareholder.

3.3. Data and Sample

Due to limitations on the availability of data, by drawing on the research of Lou et al. [31], and considering that the main groups of SMEs on the SME board and GEM board are smaller in scale, have stronger technology, and have higher growth, in this study we selected listed companies on China's SME board and GEM board as representative SMEs and collected their panel data from 2011 to 2021 as our sample. In order to ensure the quality of the data, it was necessary to process the raw data in the following steps: first, exclude financial enterprises; second, exclude ST and *ST enterprises; third, exclude suspended or delisted enterprises; fourth, exclude enterprises with missing data or those unable to record data for five consecutive years; and fifth, exclude the interference of outliers and apply winsorization to the continuous variables at the 1% and 99% quartiles. The financial data of enterprises come from the CSMAR database, the digital finance data come from the Peking University Digital Inclusive Finance Index (2011–2020), and the patent application data of SMEs were obtained by searching the China Patent Publication Bulletin of the State Intellectual Property Office according to the name of the enterprise. Descriptive statistics of the main variables are shown in Table 1.

Table 1. Descriptive statistics.

Variable Type	Variable	Symbol	Average Value	Standard Deviation	Minimum Value	Maximum Value
Explained variable	SME innovation	*lnPat*	2.1100	1.4940	0.0000	5.7070
Explanatory variable	Digital finance	*DIF*	2.2160	0.6780	0.5960	3.2160
	Coverage breadth	*DIF_CB*	2.1990	0.6510	0.5920	3.2470
	Depth of use	*DIF_UD*	2.1980	0.7080	0.6140	3.3900
	Digitization level	*DIF_DL*	2.3060	0.8250	0.2490	3.3650
Mediating variable	Financing constraints	*KZ*	0.4800	2.2770	−6.1040	5.2460
	Risk tolerance	*Zsco*	1.4310	0.8560	−1.1230	3.7920
	Information asymmetry	*Asym*	1.6000	1.1540	0.0000	3.7610
Control variable	Firm size	*Size*	21.7520	0.9270	19.9950	24.3990
	Firm age	*Age*	16.5070	5.2410	5.0000	31.0000
	Liability on asset ratio	*Lev*	0.3520	0.1820	0.0440	0.8020
	Return on assets	*Roa*	0.0400	0.0660	−0.3080	0.1940
	Fixed assets	*Fix*	0.1890	0.1260	0.0040	0.5520
	Duality	*Dual*	0.3550	0.4790	0.0000	1.0000
	Share of independent directors	*Inde*	0.3780	0.0530	0.3330	0.5710
	Ownership concentration	*Top*	0.3190	0.1360	0.0850	0.6890

4. Results

4.1. Baseline Regression Estimation Results-H1 Test

Table 2 shows the results of estimating the incentive effects of digital finance on SME innovation, controlling for industry- and year-fixed effects. In particular, column 1 does not contain control variables, column 2 includes all control variables, and columns 3–5 show the estimation results of DIF_CB, DIF_UD, and DIF_DL, respectively. The results show that the estimated coefficients for DIF are 0.5855 ($p < 0.01$) and 0.5955 ($p < 0.01$), supporting H1. This indicates that digital financial services are inclusive and accessible, fostering a

distributed business landscape and incentivizing the rapid innovation and development of SMEs. Referring to the results in column 2, for every 1-unit increase in digital finance, the logarithm of patent applications by SMEs will increase by an average of 0.5955 units.

Table 2. Estimated results of baseline regression.

Variables	(1) lnPat	(2) lnPat	(3) lnPat	(4) lnPat	(5) lnPat
DIF	0.5855 ***	0.5955 ***			
	(8.1326)	(8.2755)			
DIF_CB			0.5023 ***		
			(9.0042)		
DIF_UD				0.3391 ***	
				(5.7125)	
DIF_DL					0.0593
					(0.6600)
Size		0.3519 ***	0.3527 ***	0.3499 ***	0.3493 ***
		(17.8973)	(17.9698)	(17.7332)	(17.6643)
Age		0.0059 **	0.0062 **	0.0052 *	0.0052 *
		(1.9808)	(2.0995)	(1.7432)	(1.7493)
Lev		0.0059	−0.0061	0.0246	0.0218
		(0.0625)	(−0.0648)	(0.2617)	(0.2323)
Roa		2.5673 ***	2.5625 ***	2.5819 ***	2.6258 ***
		(11.3094)	(11.2930)	(11.3744)	(11.5662)
Fix		0.1982	0.2133 *	0.1320	0.0686
		(1.5358)	(1.6524)	(1.0252)	(0.5341)
Dual		0.0254	0.0233	0.0363	0.0501 *
		(0.8928)	(0.8187)	(1.2746)	(1.7662)
Inde		−0.8541 ***	−0.8874 ***	−0.7767 ***	−0.7576 ***
		(−3.4156)	(−3.5481)	(−3.0998)	(−3.0206)
Top		0.0368	0.0317	0.0538	0.0711
		(0.3666)	(0.3156)	(0.5358)	(0.7079)
Constant	0.8123 ***	−6.8014 ***	−6.5948 ***	−6.2070 ***	−5.5916 ***
	(5.0679)	(−14.8147)	(−14.7510)	(−13.6988)	(−11.6793)
Industry-fixed effect	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes
N	9908	9908	9908	9908	9908
R^2	0.2418	0.2944	0.2953	0.2917	0.2896

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$, *t*-test values in parentheses.

From the estimation results of control variables, Size, Age, and Roa show significant positive incentive effects on SME innovation, indicating that SMEs with stronger assets, longer duration of continuous operation, and more guaranteed net profit have better prospects for innovation development. However, Inde has a negative effect on incentivizing SMEs to innovate, because although the independent director mechanism can improve the internal governance of the enterprise, there are obstacles to its performance: it is easily affected by factors such as shareholding structure, control, and incentive constraints, and a too-high proportion of independent directors can lead to SMEs being too conservative in their innovation, which is not conducive to enhancing the quality of innovation. In addition, the estimated coefficients of Lev, Fix, Dual, and Top do not pass the 10% two-tailed test of significance, so they are not valid.

From the estimation results in columns 3–5, both DIF_CB and DIF_UD have a significant effect on incentivizing SMEs to innovate, and DIF_CB has a stronger effect, while

DIF_DL is less effective. Generally speaking, the depth of use represents the activity of users' participation in digital-finance-related business, which is an important guarantee for the function of digital finance. Although the number of digital finance users is large, some users do not use digital-finance-related businesses in depth. At the same time, some SMEs rely too much on traditional banking and neglect to use digital financial platforms. As a result, the incentive effect of depth of use on SME innovation is weak, while that of breadth of coverage is stronger. In addition, because digital technology is still in a stage of rapid development, its incentive effect on SME innovation has not yet been fully demonstrated.

4.2. Heterogeneity Analysis Results: Test of H2, H3, and H4

4.2.1. Heterogeneity Analysis Based on Ownership Structure

The entire sample was divided into two groups based on ownership structure: state-owned enterprises and private enterprises, and separate estimation tests were conducted. The results are shown in Table 3. It can be observed that the estimated coefficient for DIF in the private enterprise group is 0.6614 and is significant at the 1% level, which is 0.064 units higher compared to the state-owned enterprise group. This indicates that digital finance has a stronger incentive effect on innovation for private SMEs, supporting H2. This finding suggests that digital finance, through technology such as big data and intelligent risk control, provides more diversified financing channels and personalized financial services for private SMEs, lowering financing thresholds and costs. At the same time, digital finance enhances information transparency, boosting financial institutions' confidence in the innovation capabilities of private SMEs and enabling them to more effectively access funding and promote innovative development.

Table 3. Estimation results of heterogeneity of property rights nature.

Variables	(1) State-Owned Enterprises	(2) Private Enterprises
DIF	0.5974 **	0.6614 ***
	(2.4392)	(8.6058)
Constant	−8.4719 ***	−7.0654 ***
	(−7.0666)	(−14.1698)
Control variable	Yes	Yes
Industry-fixed effect	Yes	Yes
Year-fixed effect	Yes	Yes
N	1260	8643
R^2	0.5299	0.2775

Note: *** $p < 0.01$, ** $p < 0.05$, *t*-test values in parentheses.

4.2.2. Heterogeneity Analysis Based on Financial Regulation

We used the ratio of regional financial regulatory fiscal expenditure to the added value of the financial industry as a proxy indicator for regional financial regulation. The full sample was divided into terciles based on the intensity of financial regulation, with the sub-sample below the one-third quantile defined as weak financial regulation and the sub-sample above the two-thirds quantile defined as strong financial regulation. On this basis, we conducted grouped estimation tests, and the results are shown in Table 4. It can be observed that the estimated coefficient for DIF in regions with strong financial regulation is 0.7394 and is significant at the 1% level, while the coefficient for regions with weak financial regulation is only 0.4572. This indicates that in areas with stronger financial regulation, digital finance is more effective at stimulating SME innovation, supporting H3. This is because, in regions with stronger financial regulation, the transparency and compliance of the financial system improve, thereby enhancing the trust of SMEs in digital financial platforms. By leveraging technologies such as big data and artificial intelligence, digital finance can accurately assess credit risks within a compliant framework and lower financing

barriers, thereby reducing the bid-ask spread and transaction fee ratios for SMEs involved in innovative projects, ultimately improving transaction volumes [32]. This will help reduce liquidity and credit risks, not only providing a guarantee for the healthy development of commercial banks but also significantly stimulating innovation among SMEs.

Table 4. Estimation results of financial regulation heterogeneity.

Variables	(1) Weak Financial Regulation	(2) Strong Financial Regulation
DIF	0.4572 ***	0.7394 ***
	(3.1003)	(6.0422)
Constant	−5.2575 ***	−8.8191 ***
	(−6.4131)	(−11.2051)
Control variable	Yes	Yes
Industry-fixed effect	Yes	Yes
Year-fixed effect	Yes	Yes
N	3325	3279
R^2	0.2960	0.3282

Note: *** $p < 0.01$, *t*-test values in parentheses.

4.2.3. Heterogeneity Analysis of Marketization Degree

The full sample was divided into terciles based on the marketization index, with the sub-sample below the one-third quantile defined as low marketization and the sub-sample above the two-thirds quantile defined as high marketization. Grouped estimation tests were conducted, and the results are shown in Table 5. It can be observed that, in regions with higher marketization, the estimated coefficient for DIF is 0.6637 and significant at the 1% level, while in regions with lower marketization, the DIF coefficient is 0.5128. This indicates that in regions with higher levels of marketization, digital finance has a stronger effect on stimulating SME innovation, supporting H4. This is because, in regions with higher marketization, resource allocation is more dependent on market forces, and the financial environment is more open and competitive, leading to the rapid development of digital finance and the provision of diversified financing options. SMEs in such an environment can more easily access personalized financial services based on big data and intelligent risk control, reducing financing costs and barriers. Furthermore, the competitive pressure in marketized regions encourages SMEs to accelerate innovation, and digital finance, through flexible financial support and risk pricing, further enhances their innovation potential.

Table 5. Estimation results of marketization heterogeneity.

Variables	(1) Low Degree of Marketization	(2) High Degree of Marketization
DIF	0.5128 ***	0.6637 ***
	(4.2186)	(3.5847)
Constant	−7.0554 ***	−7.5246 ***
	(−9.0019)	(−8.3684)
Control variable	Yes	Yes
Industry-fixed effect	Yes	Yes
Year-fixed effect	Yes	Yes
N	3313	3091
R^2	0.3161	0.3215

Note: *** $p < 0.01$, *t*-test values in parentheses.

4.3. Results of Mechanism Analysis: Test of H5, H6, and H7

The results are shown in Table 6. It can be observed that, First, the estimated coefficient for DIF in column 2 is −0.4168 and is significant at the 1% level, indicating that digital finance can expand funding sources and reduce transaction costs, effectively alleviating the financing constraints faced by SMEs. In column 3, the estimated coefficient for KZ is −0.0563 and the DIF coefficient is 0.5720, with both significant at the 1% level, suggesting that financing constraints have a partial mediating effect, thus supporting H5. Digital finance, through big data and artificial intelligence technologies, accurately assesses SME credit risk and offers flexible, low-cost financing solutions, thereby lowering the high threshold of traditional financing. This facilitation of financing reduces capital constraints, enabling SMEs to obtain the necessary funds and fostering innovation in technology and products, which in turn drives overall business development.

Table 6. Estimation results of mechanism test.

Variables	(1) lnPat	(2) KZ	(3) lnPat	(4) Zsco	(5) lnPat	(6) Asym	(7) lnPat
DIF	0.5955 ***	−0.4168 ***	0.5720 ***	0.1459 ***	0.5855 ***	0.4605 ***	0.4978 ***
	(8.2755)	(−4.6971)	(7.9357)	(5.8294)	(8.1185)	(8.7672)	(6.9021)
KZ			−0.0563 ***				
			(−6.5916)				
Zsco					0.0683 **		
					(2.2294)		
Asym							0.2121 ***
							(14.8102)
Constant	−6.8014 ***	7.2886 ***	−6.3911 ***	5.2192 ***	−7.1578 ***	−12.2836 ***	−4.1966 ***
	(−14.8147)	(13.1704)	(−13.8206)	(32.0887)	(−14.4718)	(−38.8969)	(−8.7147)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	9908	9908	9908	9908	9908	9908	9908
R^2	0.2944	0.5336	0.2978	0.7529	0.2947	0.4046	0.3104

Note: *** $p < 0.01$, ** $p < 0.05$, *t*-test values in parentheses.

Additionally, the estimated coefficient for DIF in column 4 is 0.1459 and is significant at the 1% level, indicating that digital finance can reduce risk management costs, alleviate agency conflicts, and enhance SMEs' ability to handle risk and uncertainty, thereby increasing their risk tolerance. In column 5, the estimated coefficient for Zsco is 0.0683 and the DIF coefficient is 0.5855, which are significant at the 5% and 1% level, respectively, suggesting that risk tolerance has a partial mediating effect, supporting H6. Digital finance, through precise risk assessment and flexible financing products, strengthens SMEs' risk tolerance. As a result, businesses are more willing to pursue innovative projects and technological development with reduced financial pressure. The funding support and risk management provided by digital finance boost SMEs' confidence and capacity for innovation, thereby promoting their long-term development and market competitiveness.

Finally, the estimated coefficient for DIF in column 6 is 0.4605 and is significant at the 1% level, indicating that digital finance can help SMEs dynamically monitor their operational conditions and, through enhanced information screening capabilities, compel them to strictly control the quality of disclosed information, thereby increasing analysts' attention and alleviating information asymmetry. In column 7, the estimated coefficient for Asym is 0.2121 and the DIF coefficient is 0.4978, with both significant at the 1% level, suggesting that information asymmetry has a partial mediating effect, supporting H7. This demonstrates that digital finance, through big data and artificial intelligence technologies, improves the transparency and accuracy of financial information, effectively mitigating the information asymmetry prevalent in traditional financing. This allows financial institutions to more accurately assess the credit risk of SMEs, thereby providing more suitable

financing solutions. The increased transparency of information reduces financing barriers, enabling SMEs to secure the necessary funds, thus stimulating innovation in technology and products.

4.4. Robustness Test

4.4.1. Re-Estimation Test Using China Micro and Small Enterprise Survey (CMES) Data

In order to avoid the problem of bias in estimation results that could be caused by the selection of samples from listed companies, to re-test the estimation test in this study, we selected CMES data as a new sample, which is a comprehensive mapping of production and operation for 5497 micro and small enterprises in 28 provincial areas conducted by the China Household Finance Survey and Research Center of Southwestern University of Finance and Economics, and it has certain applicable value. The CMES and Peking University's Digital Financial Inclusion Index were matched to screen out the 1781 samples without control variables and the 1178 samples with control variables.

Considering the differences in the survey data indicators, most of which are 0–1 type variables, a binary probit model was constructed to carry out empirical tests as follows:

$$Innovation_{ijt} = \begin{cases} 1, Innovation^*_{ijt} > 0 \\ 0, Innovation^*_{ijt} < 0 \end{cases} \tag{4}$$

$$Innovation^*_{ijt} = \alpha_0 + \alpha_1 DIF_{jt} + Size_{ijt} + Age_{ijt} + Edu_{ijt} + Workyear_{ijt} \\ + Gove_{ijt} + Cash_{ijt} + Union_{ijt} + Location_{ijt} + \sum ind + \varepsilon_{ijt} \tag{5}$$

In model (4), i denotes enterprise, j denotes province, and t denotes year. The explanatory variable *Innovation* depends on the value of the latent variable *Innovation**; *Innovation** > 0 indicates the existence of innovative independent research and development activities in the enterprise, and *Innovation* takes the value of 1; *Innovation** < 0 indicates the absence of independent research and development activities, and *Innovation* takes the value of 0. *DIF* is an explanatory variable, which denotes the level of digital financial development in the province, and ε_{ijt} is a random perturbation term. At the same time, it is necessary to control for the variables firm size (*Size*), firm age (*Age*), education of the enterprise owner (*Edu*), number of years the owner has been managing the enterprise (*Workyear*), whether the government gives subsidies to the enterprise or not (*Gove*), whether the enterprise increased its registered capital or not (*Cash*), whether the enterprise joined an industry association or not (*Union*), whether the enterprise is located in a science and technology park or not (*Location*), and the industry dummy effect ($\sum ind$).

Table 7 reports the estimation results using the CMES data stability test, where column 1 has no control variables added and column 1 has all control variables added. It can be found that the estimated coefficients of DIF are 0.2782 and 0.2843, passing the two-tailed test of significance at 5% and 10%, respectively, suggesting that digital financial development has a significant effect on incentivizing SMEs to innovate and develop, meaning the main core findings are robust.

Table 7. Estimation results using CMES data stability test.

Variables	(1) *Innovation*	(2) *Innovation*
DIF	0.2782 **	0.2843 *
	(2.3105)	(1.7857)
Constant	0.0564	−0.0021
	(0.2317)	(−0.0036)
Control variable	No	Yes
Industry-fixed effect	Yes	Yes
N	1781	1178
Pseudo R^2	0.0445	0.0762

Note: ** $p < 0.05$, * $p < 0.1$, z-test values in parentheses.

4.4.2. Replacement of Explanatory Variables

In order to exclude the problem of unbiased estimation results caused by variable selection, in this study, we adjusted the proxy indicators of SME innovation for the explanatory variables, replacing them with the number of invention patent applications (ln*Ipat*), number of utility model patent applications (ln*Upat*), number of design patent applications (ln*Dpat*), and the ratio of R&D expenditures to main business income (ln*Rds*), and re-conducted the estimation test, and the estimation results are shown in Table 8. It can be found that the estimated coefficients of DIF are all significantly positive and significant at least at the 5% level. In terms of impact validity, the effect of digital finance on SMEs' invention patent applications is the highest, reaching 0.6737, which indicates that the innovation incentive effect of digital finance is mainly in pursuit of quality rather than quantity. Overall, the robustness of the key findings is again confirmed.

Table 8. Estimation results with replacement of explanatory variables.

Variables	(1) ln*Ipat*	(2) ln*Upat*	(3) ln*Dpat*	(4) ln*Rds*
DIF	0.6737 ***	0.1493 **	0.3213 ***	0.3842 ***
	(10.6951)	(2.3867)	(6.7813)	(9.2774)
Constant	−7.4164 ***	−4.6704 ***	−3.9422 ***	2.1194 ***
	(−18.1012)	(−11.6434)	(−11.7562)	(8.5065)
Control variable	Yes	Yes	Yes	Yes
Industry-fixed effect	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes
N	9908	9908	9908	9300
R^2	0.2299	0.3503	0.1740	0.4885

Note: *** $p < 0.01$, ** $p < 0.05$, *t*-test values in parentheses.

4.4.3. Transforming the Econometric Model

In this study, there are two ways to transform the econometric model. The first one is to use high-dimensional fixed effects, and then, on the basis of the fixed "industry–year" combination, add enterprise-fixed effects and "industry × year"-fixed effects in turn, and the estimation results are shown in Table 9 and columns 1 and 2. It can be found that the estimated coefficients of DIF are still positive, and all of them pass the significance test at 5%. The second way is to construct a dynamic panel model with lag 1 and lag 2, and the estimation results are shown in Table 9 and columns 3 and 4. The results show that the lagged terms L_1.ln*Pat* and L_2.ln*Pat* are both significantly positive, indicating that the dynamic panel model is adaptable. Meanwhile, the estimated coefficient of DIF is significant at 0.1758, indicating that digital finance can effectively incentivize SMEs to innovate under the premise of considering the potential influencing factors, further proving that the core findings are robust.

Table 9. Estimation results of transformed econometric model.

Variant	High-Level Fixed Effect		Dynamic Panel Model	
	(1) ln*Pat*	(2) ln*Pat*	(3) ln*Pat*	(4) ln*Pat*
L_1.ln*Pat*			0.7496 ***	0.5616 ***
			(93.3152)	(39.1405)
L_2.ln*Pat*				0.2752 ***
				(18.7553)
DIF	0.4194 **	0.4058 **	0.1947 ***	0.1758 ***
	(2.3226)	(2.0615)	(3.7403)	(3.2956)
Constant	−2.5064 **	−2.9367 ***	−1.9653 ***	−1.5916 ***
	(−2.4956)	(−2.7635)	(−5.9770)	(−4.4885)
Control variable	Yes	Yes	Yes	Yes

Table 9. *Cont.*

Variant	High-Level Fixed Effect		Dynamic Panel Model	
	(1) ln*Pat*	**(2)** ln*Pat*	**(3)** ln*Pat*	**(4)** ln*Pat*
Industry-fixed effect	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes
Firm-fixed effect	Yes	Yes	No	No
Industry × year-fixed effect	No	Yes	No	No
N	9908	9814	8464	7047
R^2	0.7488	0.7606	0.6768	0.7110

Note: *** $p < 0.01$, ** $p < 0.05$, *t*-test values in parentheses. L1, lag 1; L2, lag 2.

4.5. Endogeneity Analysis

In order to alleviate the problem of endogeneity causing biased estimation results, the instrumental variable method was further used to verify the impact of digital finance on SME innovation capacity. Referring to the approach of Wei et al. [33], we selected two indicators of a city's spherical distance from Hangzhou multiplied by the national digital finance mean ($Dist_{Hangzhou} \times Mean\_DIF$) and its spherical distance from the provincial capital city multiplied by the national digital finance mean ($Dist_{provincial\ capital\ city} \times Mean\_DIF$) as dual instrumental variables. The reason is that, first, Alipay, as the leader in digital financial ecology, is a company headquartered in Hangzhou, which has more abundant digital financial development, and it can be assumed that the closer the city to Hangzhou, the greater the effect of digital finance radiating and developing faster. Similarly, the capital city of a province is in a leading position in digital finance development, and the closer the area is to the capital city, the faster the digital finance should develop. Therefore, these two instrumental variables are closely related to the development of digital finance. Second, the variables incorporating geographic distance are more exclusive and exogenous.

Table 10 reports the estimation results of the endogeneity discussion. First, from the results of the first stage, the estimation results of $Dist_{Hangzhou} \times Mean\_DIF$ and $Dist_{provincial\ capital\ city} \times Mean\_DIF$ are significantly negative, which verifies the conclusion that the farther away from Hangzhou and provincial cities, the weaker the level of digital financial development of the region. Secondly, from the results of the second stage, the *p*-value of the IV unidentifiable test is less than 0.1, the F-value of the weak IV test is much larger than the 10% distortion level of 19.93, and the *p*-value of the IV over-identified test is larger than 0.1, which indicates that the instrumental variables are valid and there is no over-identification problem overall. The estimated coefficients of *DIF* remain significantly positive with mitigated endogeneity, indicating that digital finance does incentivize SMEs to innovate.

Table 10. Estimation results of instrumental variable regression.

Variable	**(1)** Phase I	**(2)** Phase II
DIF		1.2822 *** (2.8318)
$Dist_{hangzhou} \times Mean\_DIF$	−0.0053 *** (−13.6564)	
$Dist_{provincial\ capital\ city} \times Mean\_DIF$	−0.0249 *** (−16.9458)	
IV unrecognizable test *p*-value	0.0000	
IV weak test F-value	832.936	
IV over-recognition test *p*-value	0.6232	
Control variable	Yes	Yes
Industry-fixed effect	Yes	Yes
Year-fixed effect	Yes	Yes
N	9908	9908
R^2	0.9956	0.0064

Note: *** $p < 0.01$, *t*-test values in parentheses.

5. Conclusions, Recommendations, and Research Outlook

5.1. Conclusions

With the rapid development of the digital economy, digital finance has provided significant opportunities for the innovative growth of SMEs. In this study, we empirically examined the effectiveness, heterogeneity characteristics, and transmission mechanisms of digital finance in stimulating SME innovation, using data from companies listed on China's SME and ChiNext boards between 2011 and 2021. A series of valuable conclusions were obtained, as follows:

(1) Digital finance significantly stimulates SME innovation. Among its sub-dimensions, breadth of coverage, depth of usage, and degree of digitalization show notable differences in their effectiveness in promoting SME innovation. Specifically, breadth of coverage has the strongest impact, followed by usage depth, while the effect of digitalization is not statistically significant.

(2) The impact of digital finance on SME innovation exhibits a certain degree of heterogeneity. Specifically, digital finance has a more significant effect on fostering innovation among privately owned SMEs. Additionally, in regions with stronger financial regulation and higher levels of marketization, the stimulating effect of digital finance on SME innovation is more pronounced.

(3) The mediation effect test reveals that digital finance can indirectly stimulate SME innovation through three pathways: alleviating financing constraints, enhancing risk tolerance, and addressing information asymmetry.

5.2. Recommendations

Based on the main conclusions of this study, the following suggestions are put forward:

(1) Combine digital financial scenarios to promote the innovative development of SMEs. Firstly, by constructing digital financial application scenarios, driving the free flow of financial resources, giving full play to the "survival of the fittest" mechanism of the capital market, selecting high-value innovation projects for SMEs, actively providing credit support, and accelerating the transformation of scientific and technological achievements. Secondly, through digital financial application scenarios, we can broaden financing channels, weaken agency conflicts, supervise managers' controlling behaviors, and build an open and inclusive governance system to strengthen SMEs' substantive innovation decisions.

(2) Focus on the heterogeneous characteristics of digital finance to stimulate SME innovation. Specifically, it is necessary to base innovation on local resources, break the closed market situation, break market segmentation, take the initiative to open the market, standardize the order of market transactions, and drive the flow of digital financial resources to private SMEs, especially those with strong demand for capital and innovation initiatives. At the same time, we should focus on digital financial regulation, guide the healthy development of digital finance, and fully guard against the risks of digital finance to empower SME innovation.

(3) Unclog the conduction path of digital finance to incentivize SME innovation. First, improve the credit guarantee mechanism for SMEs by optimizing the credit structure, lowering the collateral threshold, and building a risk-sharing system. Secondly, with the help of cash, equity, and options, incentivize the management of SMEs to overcome short-sighted thinking, bravely bear innovation risks, strengthen investment in high-risk innovation projects, and obtain long-term profit returns. Finally, the information screening function of digital financial platforms should be utilized to ensure information traceability, promote SMEs to carry out substantive innovation activities, shorten the trial and error time of innovation, and improve the quality of innovation.

5.3. Research Outlook

It is important to note that this study has certain limitations that warrant further exploration. First, the study relied on short-term panel data, which may not fully capture the long-term dynamic effects of digital finance on SME innovation. Second, the measurement of digital finance and SME innovation could be further refined, particularly by incorporating more detailed indicators of technology adoption and firm-level innovation outcomes. Third, future research could explore the roles of specific digital finance tools, such as blockchain or AI-driven risk assessment, in fostering SME innovation. Lastly, the interaction between digital finance and other external factors, such as innovation policy support and SME access to technology standards, remains underexplored. Addressing these gaps could offer valuable insights for more comprehensive policy recommendations.

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