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Digital Finance and Private Enterprise Innovation in China: Impacts, Mechanisms, and Environmental Changes

Abstract. *This study thoroughly examines the influence of digital finance on innovation among private firms, utilising data from private companies listed on the Shanghai and Shenzhen A-share markets over the period 2011-2021. It explores the nonlinear impacts of digital finance on both the quality and boundary of innovation, taking into account changes in external and internal environments. The study reveals that digital finance acts as a catalyst, motivating private enterprises to boost their R&D investments and improve their innovation outcomes. By easing financial constraints, providing supplementary support, and reducing managerial expenses, digital finance plays a crucial role in driving innovation within private enterprises. Particularly noteworthy is the stronger positive influence of digital finance on innovation observed in private enterprises situated in inland regions and those operating in high-tech sectors. Furthermore, the analysis uncovers that heightened economic policy uncertainty can impede the ability of digital finance to stimulate innovation expansion within private enterprises, potentially leading to a dampening effect. When corporate equity concentration is low, digital finance incentivises private enterprises to enhance the quality of their innovations. Conversely, in cases of higher equity concentration, digital finance encourages private enterprises to broaden their innovation boundaries.*

Keywords: *digital finance, private enterprise innovation, innovation boundary, economic policy uncertainty, equity concentration.*

JEL Classification: D22, D80, L20.

1. Introduction

During the 45 years of reform and opening up in China, the private economy has witnessed rapid expansion. Within China's platform economy, sectors such as new energy vehicles, photovoltaics, and others have not only caught up but also taken the lead in global advancements. Private enterprises have demonstrated

significant growth potential, emerging as a critical component of China's economy, a key driver of industrial transformation and upgrade, and a major force behind scientific and technological innovation. In recent times, Chinese private enterprises have increased their investments in research and development (R&D), resulting in a continuous enhancement of their innovation capabilities. State Intellectual Property Office (SIPO) and the All-China Federation of Industry and Commerce (ACFIC) data reveal that the collective R&D expenditure of the top 1,000 private enterprises in terms of R&D investments reached 1.24 trillion yuan in 2022, constituting 40.14% of the nation's total R&D investments and 51.75% of corporate R&D support – an increase of 14.37% year-on-year. In 2022, the number of patent applications from national private enterprises increased to 1,475,000, marking a significant 17.4% increase from the previous year. Notably, amongst these applications, only about 30% were for invention patents – a representation of "high-quality innovation." This underscores the pressing need for private enterprises to elevate the quality and scope of their innovations. Given the heightened uncertainties in both domestic and international economic landscapes, the sustainable development of China's economy hinges on private enterprises breaking free from the "high input, low quality" innovation model and overcoming technological barriers imposed by Western nations. Successful escape from these constraints is imperative to foster high-quality economic growth and ensure sustained innovation and competitiveness in the global arena.

For private enterprises grappling with substantial demand for external financing and facing frequent rejections from conventional financial institutions, the challenges posed by the characteristics of "high investment, long cycle, and high risk" in innovation not only hinder their ability to engage in high-quality innovative endeavours but also often trap them in the quagmire of "low innovation quality and stagnant innovation boundaries." This cycle of constrained innovation quality and stagnant boundaries can easily ensnare enterprises. Digital finance, incorporating cutting-edge technologies like big data, cloud computing, 5G, and others, is revolutionising traditional financial services and significantly impacting private enterprise innovation. On one front, the rise of digital finance has given birth to financial technology powers such as Ant Financial Services. These entities not only address the perennial issue of "challenging and costly financing" for private enterprises but also propel these enterprises – long overlooked by traditional financial establishments – onto a "financing expressway." This shift enables them to traverse the final stretch and break through barriers to innovation (Liu et al., 2024). Moreover, digital finance leverages big data to fortify financial systems. By utilising the information platforms constructed through big data, digital finance effectively navigates market insights, dismantles information silos between fund providers and seekers, mitigates resource mismatches, reduces management overheads stemming from information asymmetry, and facilitates private enterprises in executing top-tier innovation initiatives, thereby providing crucial support for high-quality innovation endeavours.

Existing research has delved extensively into two critical realms: digital finance and private enterprises. Researchers have undertaken a plethora of theoretical and empirical studies on these subjects to illuminate various facets of their interactions. Many scholars cut from the macro perspective to explore the impact of digital finance on regional economic development and rural revitalisation and urban green innovation (Zhang et al., 2023). Some other scholars focus on the micro level, discussing the impact of digital finance on financial literacy, enterprise financing, and individual entrepreneurship (Yang et al., 2023). Some other scholars focus on the micro level and discuss the impact of digital finance on financial literacy, enterprise financing, individual entrepreneurship, etc., which clarifies the effect of digital finance on the micro level. As for private enterprises, scholars focus on the financing constraints, executive governance, executive governance, social responsibility, and non-compliance behaviour (Zhang et al., 2023). Some scholars have analysed the issues of mixed ownership mergers and acquisitions, informal system, and government-enterprise linkage (Song et al., 2015), focusing on the ways and mechanisms of private enterprise innovation. In addition, some scholars link the two important themes of digital finance and private enterprises together, and find that digital finance can effectively alleviate the financing constraints of private enterprises and significantly promote the improvement of total factor productivity of private enterprises and contribute to the healthy growth of private enterprises (Jin et al., 2024). Despite these insights, only a limited number of studies have scrutinised the relationship between digital finance and private enterprise innovation, with even fewer studies refining our understanding of private enterprise innovation dynamics. This underscores a significant research gap that warrants further exploration and analysis to comprehensively grasp the intricate interplay between digital finance and private enterprise innovation.

The intersection of financial and technological innovations has given rise to digital finance, a potent force shaping the landscape of private enterprise innovation. This sophisticated amalgamation plays a pivotal role in propelling private enterprises towards high-quality development. However, the intricate dynamics underlying this relationship necessitate a nuanced understanding of how digital finance influences private enterprise innovation and whether its impact varies across different internal and external enterprise environments. As a multifaceted endeavour, can private enterprise innovation indeed achieve high-quality evolution under the impetus of digital finance? Unravelling the mechanism through which digital finance stimulates private enterprise innovation is crucial in comprehending this synergy. Furthermore, investigating how changes in internal and external enterprise environments modulate the effect of digital finance on private enterprise innovation is paramount. By addressing these questions, we not only deepen our comprehension of the interconnectedness between digital finance evolution and private enterprise innovation but also inject fresh momentum into catalysing the high-quality development of private enterprises. To shed light on these inquiries, this study leverages data from Chinese A-share listed private enterprises in Shanghai and Shenzhen spanning from 2011 to 2021 as the research sample. Through empirical

analysis, the research endeavours to elucidate the impact of digital finance on private enterprise innovation, with a specific focus on innovation quality and boundaries. By delineating the pathways and mechanisms through which digital finance shapes private enterprise innovation, the study aims to unveil the potential nonlinear relationships between digital finance and private enterprise innovation within the context of varying internal and external enterprise environments. Through this empirical exploration, the study seeks to unravel the intricate interplay between digital finance and private enterprise innovation, paving the way for a deeper understanding of their symbiotic relationship and offering valuable insights into fostering the high-quality development of private enterprises in the digital age.

The potential marginal contributions of this paper compared to existing studies are outlined as follows. First, a novel research perspective. This paper introduces a fresh research perspective by honing in on private enterprise innovation, taking into consideration both the process and outcomes of innovation activities. By delving into the influence of digital finance on private enterprises' R&D investments, innovation quantity, quality, and boundaries, this study broadens and deepens the existing research landscape. The comprehensive exploration of these facets enriches the understanding of how digital finance impacts the innovation dynamics of private enterprises. Second, comprehensive mechanism exploration. An analytical framework encompassing financing constraints, subsidies, and management costs of private enterprises is integrated into this study, facilitating an in-depth examination of the internal workings and tangible outcomes of digital finance on private enterprise innovation. By delving into the intricate interplay between digital finance and these critical factors, this paper offers a comprehensive exploration of the mechanisms driving innovation within private enterprises. Third, reasonable research expansion. This paper expands the research scope by incorporating macroeconomic policy uncertainty and micro-enterprise equity concentration to characterise the external and internal environments of private enterprises. Through empirical analysis, the study investigates how these internal and external factors influence the relationship between digital finance and private enterprise innovation. By providing insights into the impact of the enterprise environment on innovation dynamics, this research equips digital finance to better adapt to the prevailing conditions and effectively support private enterprise innovation efforts. The findings of this study could serve as a robust foundation and practical guide for enhancing the role of digital finance in fostering innovation within private enterprises.

2. Research hypotheses

In the contemporary era of burgeoning digital technology, the pivotal role of digital finance in propelling the growth of private enterprises and fostering the high-quality development of the private economy has become increasingly evident (Li & Hu, 2024). Digital finance serves as a crucial driver in this landscape by facilitating the alignment of financial service supply and demand. Through the utilisation of advanced technologies such as big data and cloud computing, digital finance

effectively overcomes traditional constraints related to geography and temporality. This breakthrough enables a broadening of the traditional financial service scope, mitigating biases toward ownership and scale that are inherent in conventional financial models. Consequently, digital finance ensures that convenient and efficient financial services are more readily accessible to private enterprises. Furthermore, digital finance plays a vital role in aligning product market dynamics. Leveraging Internet platforms, digital finance eradicates barriers between product supply and demand, fostering enhanced two-way communication through innovative matching pathways and price mechanisms (Lu et al., 2024). This enhanced connectivity not only diversifies consumer demand but also provides private enterprises with an expanded arena for innovation, thereby catalysing their potential for creativity and advancement. In essence, the following hypothesis is put forward.

Hypothesis 1: *Digital finance can incentivise innovation in private enterprises*.

The traditional financial system in China is making strides towards improvement; however, financing constraints continue to pose significant challenges for private enterprises' innovation endeavors. Through the integration of modern information technology, digital finance has undergone a transformative evolution, revamping traditional financial services. This evolution enables real-time tracking and supervision of financial services, effectively addressing issues like information asymmetry and moral risks (Kong et al., 2022). Simultaneously, digital finance reduces information and transaction costs during the financing processes of private enterprises, thus alleviating their financial constraints. This shift has introduced a range of new and efficient financial instruments, repositioning market investors' attention toward private enterprises with lower risk tolerance (Demertzis et al., 2018). By enhancing investors' risk appetite and enthusiasm for private enterprise investments, digital finance expands the horizons of private enterprises and diversifies their financing avenues. The synergy between modern information technology and digital finance emerges as a crucial enabler in diminishing private enterprises' financing limitations and nurturing their innovative capacities. Therefore, this paper posits the following hypothesis:

Hypothesis 2: *By alleviating corporate financial constraints, digital finance can promote private enterprise innovation.*

When private firms experience lower marginal returns on innovation compared to social marginal returns, the resulting lack of incentives for innovation necessitates government interventions, such as subsidies, to counterbalance the absence of market mechanisms (Shao & Wang, 2023). In theory, government subsidies serve not only to directly allocate economic resources to the economy but also to society at large. Theoretically, these subsidies not only channel economic resources directly to private enterprises, but also enhance these enterprises' access to external financing by signaling their credibility to the capital market. However, the practical implementation of this ideal has faced obstacles. The significant information asymmetry between the government and private enterprises poses challenges, impeding the government's ability to effectively evaluate and select deserving

private enterprises. Consequently, numerous private enterprises with untapped innovative potential find themselves excluded from benefiting from government subsidies (Liu et al., 2024). Digital finance integrates cutting-edge digital technologies like big data and cloud computing with traditional financial services, enhancing market information transparency and mitigating instances of market failure. It addresses issues of resource mismatch stemming from market failures, thereby improving resource allocation efficiency. Through the utilisation of digital finance, governmental entities can accurately identify high-quality recipients for subsidies and monitor the utilisation of these funds, fostering a conducive environment for private enterprises to engage in innovation (Feng et al., 2022). This proactive screening and monitoring mechanism incentivises private enterprises to innovate. Accordingly, this paper proposes the following hypothesis:

Hypothesis 3: By enhancing support for enterprises to obtain subsidies, digital finance can boost private enterprise innovation.

The theory of "free cash flow" posits that enterprise managers often tend to embark on large-scale projects with high spending in order to maximise benefits. However, this practice not only escalates business management costs but also depletes cash flow, leading to limited resources for innovation (Jensen, 1986). In contrast to state-owned enterprises, private enterprises exhibit a closer alignment between ownership and management rights, with fewer constraints on controlling shareholders, facilitating the potential emergence of a "one share dominance" scenario. The issue of agency conflicts amplifies risks for private enterprises, escalating management costs, and impeding their innovation endeavors. Digital finance plays a pivotal role in optimising enterprise supervision and incentive mechanisms, thereby curbing managerial opportunism and mitigating principal-agent conflicts within organisations. By offering private enterprises efficient digital tools and platforms, digital finance significantly reduces the expenses associated with managing business processes, data, and resources (Lu et al., 2024). This cost reduction serves to invigorate private enterprises, fostering a heightened willingness for research and development (R&D) and driving innovation efforts within these entities. In light of these insights, this paper posits the following hypothesis:

Hypothesis 4: By reducing the management costs, digital finance can promote private enterprise innovation.

Despite transcending the constraints of geographic boundaries, the influence of digital finance on private enterprise innovation is intricately tied to the varying levels of regional development. China, as a vast nation, exhibits notable disparities among regions in terms of population, industrial composition, economic advancement, and the status of digital finance evolution. This diversity extends to the development trajectory and maturity of digital financial services across different regions as well. Notably, China's coastal zones stand out for their heightened economic prosperity, robust infrastructure, and concentration of enterprises with substantial capabilities, thereby affording private entities in these areas access to superior financial solutions. In contrast, the relatively underdeveloped economic landscape of the inland regions

often acts as a barrier to fully leveraging the advantages offered by digital finance. This economic disparity can impede the realisation of digital finance benefits to their full potential in inland areas (Liao et al., 2022). Consequently, the impact of digital finance on private enterprise innovation is likely to exhibit variations between coastal and inland regions.

Enterprise innovation is intricately connected to the industry's business scope. Private enterprises in high-tech sectors, characterised by their knowledge and technology intensity, face fierce market competition necessitating continuous innovation efforts. These enterprises exhibit a strong demand for innovation, which comes with a challenging and high threshold (Li et al., 2023). On the contrary, private enterprises in non-high-tech industries prioritise sustainable operation over extensive innovation, focusing on reducing production costs, expanding sales channels, and refining product processes. Their motivation for high-quality innovation activities tends to be comparatively lower. Consequently, the impact of digital finance on innovation varies between private enterprises in high-tech and non-high-tech industries. In summary, the following hypotheses are proposed:

Hypothesis 5a: *There are differences in the impact of digital finance on innovation in private enterprises between coastal and inland regions.*

Hypothesis 5b: *The impact of digital finance on innovation in private enterprises differs between high-tech and non-high-tech industries.*

3. Methodology

To investigate the influence of digital finance on private enterprise innovation, we establish the subsequent two-way fixed-effects model.

$$Innovation_{i,t} = \alpha + \beta Digit_{i,t} + \boldsymbol{\theta} \sum X_{i,t} + \mu_i + \upsilon_t + \varepsilon_{i,t} \tag{1}$$

where i and t denote private enterprise and year, respectively; $Innovation_{i,t}$ is the explained variable "private enterprise innovation", which involves R&D investment, innovation quantity, innovation quality, and innovation boundary of private enterprises; $Digit_{i,t}$ is the core explanatory variable "digital finance", which characterises the level of digital financial development in the city where private enterprises are located; $\sum X_{i,t}$ represents the control variables, encompassing characteristics at both the private enterprise and city levels; μ_i, υ_t, and $\varepsilon_{i,t}$ denote the individual fixed effect, the time fixed effect, and the random error, respectively.

Equation (1) reflects the direct impact of digital finance on private enterprise innovation. To investigate the mechanism through which digital finance influences private enterprise innovation, we construct the following intermediary effect model:

$$Innovation_{i,t} = \alpha + \beta Digit_{i,t} + \delta_1 Med_{i,t} + \delta_2 Digit_{i,t} \times Med_{i,t} + \boldsymbol{\theta} \sum X_{i,t} + \mu_i + \upsilon_t + \varepsilon_{i,t} \tag{2}$$

where $Med_{i,t}$ is the mediating variable, which indicates the financing constraints, subsidies received, and management costs of private enterprises; $Digit_{i,t} \times Med_{i,t}$ is

the interaction term between the core explanatory variable digital finance and the mediating variable; and The definitions of the remaining variables are consistent with those in Equation (1).

To delve deeper into the impact of the internal and external environments of private enterprises on the correlation between digital finance and private enterprise innovation, we formulate a panel threshold regression model. Economic policy uncertainty and enterprise equity concentration serve as the threshold variables, enabling an empirical examination of the asymmetric relationship between digital finance and private enterprise innovation. As an illustration, the estimated model of the single threshold regression is depicted in equation (3):

$$Innovation_{i,t} = \alpha + \beta_1 \cdot I(En_{i,t} < \gamma)Digit_{i,t} + \beta_2 \cdot I(En_{i,t} > \gamma)Digit_{i,t}$$
$$+ \mathbf{\theta}\sum X_{i,t} + \mu_i + \upsilon_t + \varepsilon_{i,t} \tag{3}$$

where $En_{i,t}$ represents the threshold variable; γ represents the threshold value to be estimated; β_1 and β_2, respectively, represent the response coefficients of digital finance when the threshold variable is below or above the threshold value; the remaining variables are consistent with those in Equation (1).

4. Data

This study utilises data from Chinese Shanghai and Shenzhen A-share listed private enterprises spanning from 2011 to 2021 as the research sample. Financial indicators at the enterprise level and R&D investment indicators are sourced from the CSMAR database. Data from prominent databases like "Tonghuashun Finance" and "Wind Consulting" are employed to ensure data accuracy. Private enterprise patent data is sourced from the State Intellectual Property Office's enterprise invention patent database, containing comprehensive information such as patent application dates, types, names, IPC classification numbers, and applicant details of listed companies. Variables measuring economic policy uncertainty are sourced from the Economic Policy Uncertainty Index (EPU), a collaborative publication by Stanford University and the University of Chicago. City-level data primarily stem from previous editions of the China Urban Statistical Yearbook. To bolster the accuracy of the estimation outcomes, the data undergo the following processes: (1) exclusion of private enterprises in the financial sector; (2) exclusion of private enterprises categorised as ST, *ST, and PT; and (3) exclusion of private enterprises with substantial missing data on crucial variables. Finally, 19,754 observations for 2,204 private enterprises were obtained.

The explained variable "private enterprise innovation" encompasses various facets of private enterprises' innovative activities, including R&D investment, innovation quantity, innovation quality, and innovation boundary. (1) R&D investment. Private enterprises' R&D investment (RD) is quantified by the ratio of R&D investment to the main business revenue. (2) Innovation quantity. The quantity of innovation of private enterprises ($Inno1$) is gauged by the total count of new patents introduced by enterprises within a year. To handle instances where some

private enterprises may have zero new patent applications in a given year, we adopt a logarithmic transformation of the total number of patents. This involves adding one to the total count of new patents and then taking the natural logarithm. (3) Innovation quality. To evaluate the innovation quality of private enterprises ($Inno2$), we leverage the patent applications in new technology fields. By utilising the International Patent Classification (IPC) system to categorise patent technology fields, we establish the "existing technology pool" of private enterprises. Patents are classified as either belonging to existing technology fields or new technology fields based on their IPC numbers. This process enables the distinction between patents in new and existing technology fields, assisting in determining the number of annual patent applications in new technology fields. (4) Innovation boundary. Drawing inspiration from Shen et al. (2023), a methodology akin to the Herfindahl Index is employed to assess the innovation boundary of private enterprises ($Inno3$). This calculation method considers whether the distribution of technological innovation fields of private enterprises is "concentrated" or "decentralised," reflecting changes in their innovation boundary. The indicator accounts for both the type and number of technological innovation fields. A higher value of the indicator indicates a more diversified distribution of technological innovation fields and a broader innovation boundary. The calculation is as follows:

$$Bound = 1 - \sum \phi^2$$

where ϕ denotes the proportion of a specific type of IPC number among all patents applied by private enterprises in a year.

The core explanatory variable "digital finance" ($Digit$) is measured by the Digital Financial Inclusion Index of China's prefecture-level cities, which is jointly compiled by the Digital Finance Research Center of Peking University and Ant Financial (Guo et al.,2020). This index partially alleviates the scarcity of digital finance data in China and is highly authoritative.

The intermediary variables pertain to three key aspects concerning private enterprises: financing constraints, access to subsidies, and management costs. First, financing constraints (FC). Following the approach outlined by Whited & Wu (2006), the WW index is formulated to gauge the financing constraints faced by private enterprises. Second, access to subsidies (SUB). The ratio of government subsidies to the total assets of private enterprises is employed to evaluate their access to subsidies. This metric encompasses various forms of government support for private enterprises, including scientific research funding, bonuses, tax incentives, industrial support, technological enhancements, and talent acquisition. Third, management costs (MF). The management cost of private enterprises denotes the proportion of the enterprise's management expenses to its main business revenue. This metric sheds light on the financial resources allocated towards managing the operations of the enterprise.

The threshold variables in this study encompass the external and internal environments influencing private enterprises, characterised by economic policy uncertainty and corporate equity concentration, respectively. First, economic policy

uncertainty. We use the Economic Policy Uncertainty (EPU) index for China crafted by Baker et al. (2016). This index is created through text retrieval and filtering techniques, leveraging the South China Morning Post (SCMP) for news report extraction. The monthly economic policy uncertainty values are aggregated using the annual arithmetic mean, providing an annual measure of economic policy uncertainty. Second, corporate equity concentration. Equity concentration is a pivotal indicator of both the equity distribution status of private enterprises and the strength of their structure and stability. In this study, the equity concentration of private enterprises (Top) is measured using the percentage of shareholding held by the largest shareholder in the total shares of the enterprise.

The control variables cover both the enterprise and city levels. Referring to Hall et al. (2016), the control variables at the enterprise level are selected as enterprise size, age, return on assets, Tobin's Q, tangible assets ratio, cash flow ratio, and leverage ratio. The enterprise size ($Size$) is measured by the natural logarithm of the total assets of private enterprises at the end of the year. The enterprise age (Age) is calculated from the year of establishment, represented by the natural logarithm of the difference between the observation year and the founding year of the private enterprise plus one. The asset return rate (Roa) is measured by the ratio of corporate net profit to total assets. Tobin's Q ($Tobin$) is measured by the ratio of the the sum of equity market value and the net debt market value to the total assets, indicating investment and growth opportunities. The Tangible Asset Ratio ($Tangi$) is measured by the proportion of tangible assets to total assets, reflecting the structure of tangible and intangible assets. The cash flow ratio (Cf) is measured by the proportion of cash flow from operating and investing activities to total assets of private enterprises, and is used to describe the capital status of private enterprises. City-level control variables include: population size (Pop), which is the natural rate of population growth at the end of the year, and the degree of economic development (Gdp), which is the natural logarithmic value of the GDP of the city where the firm is located.

5. Empirical results

5.1 Baseline regression

Table 1 presents the outcomes of the benchmark regression analysing the impact of digital finance on innovation within private enterprises. The regression coefficients associated with digital finance in columns (1)-(2) exhibit positive values and clear significance at the 1% and 10% levels, respectively. This suggests a substantial increase in both R&D investments and innovative outputs within private enterprises due to digital finance, thus confirming Hypothesis 1. Conversely, the regression coefficients for digital finance in columns (3)-(4) of Table 1 indicate positive values, but do not attain statistical significance. This implies that while digital finance may stimulate innovation within private enterprises, it may not

effectively enhance the quality of their innovations or expand the boundary of their innovative activities.

Table 1. Baseline regression results

Variable	(1) R&D investment	(2) Innovation quantity	(3) Innovation quality	(4) Innovation boundary
Digit	0.1126***	0.2488*	0.0634	0.0219
	(0.0234)	(0.1341)	(0.0925)	(0.0221)
Control variables	yes	yes	yes	yes
Firm	yes	yes	yes	yes
Year	yes	yes	yes	yes
Observation	17,181	18,893	18,893	18,893
R^2	0.8358	0.7834	0.6669	0.7000
Adjust R^2	0.8019	0.7414	0.6024	0.6419

Note: *, **, and *** indicate 10%, 5%, and 1% significance levels, respectively; standard errors are in parentheses.

Source: Authors' processing.

5.2 Endogeneity check

Typically, private enterprise innovation does not exert a significant impact on the overall advancement of digital finance within cities, and there appears to be no apparent issue of reverse causality in the logical framework. Nevertheless, the credibility of the benchmark regression findings could potentially be influenced by undisclosed variables. For example, specific industrial policies could influence both the progress of digital finance and the innovation activities of private enterprises. This omission of pertinent variables could introduce some bias into the estimation of coefficients.

The instrumental variables approach serves as a suitable method for addressing the potential endogeneity issues outlined earlier. In studies focusing on digital finance as a core explanatory factor, three commonly utilised instrumental variables are geographic distance, historical information, and Bartik measures calculated through the Shift-share method. For this study, the two instrumental variables chosen are historical information and Bartik.

Firstly, inspired by Nunn & Qian (2014), the product of the number of telephones per 100 individuals, the number of post offices per million people in 1995, and the lagged one-period national Internet penetration rate form the initial instrumental variable for digital finance ($iv1$). This choice is grounded in the notion that regions with a rich history of landline penetration and post office presence are likely to exhibit more advanced digital finance development today, satisfying the correlation requirement. Moreover, historical data are assumed to have no direct impact on current innovative behaviours of individual private enterprises, thus meeting the exogeneity criterion.

Secondly, following insights from Goldsmith-Pinkham et al. (2020), the second instrumental variable ($iv2$) is formulated using the Bartik method. The exogeneity of Bartik IV may stem from either the exogeneity of shares or the exogeneity of shocks, with the exogeneity of shocks being relatively easier to fulfil than that of shares. When shocks meet the exogeneity condition, Bartik IV can be consistently estimated even if shares are somewhat endogenous. In this study, the initial share (share) corresponds to the city-industry level share of the country's computer usage, computed based on 2004 as the reference year, while the shock component (shift) involves the annual national growth rate of Internet users. This setup enhances the exogeneity of the instrumental variables in a more manageable manner.

Table 2. Estimation results based on the IV approach

Variable	(1) R&D investment	(2) Innovation quantity	(3) Innovation quality	(4) Innovation boundary
Digit	0.0061***	0.0083*	0.0288	0.2182
	(0.0023)	(0.0045)	(0.0202)	(0.2416)
Control variables	yes	yes	yes	yes
Firm	yes	yes	yes	yes
Year	yes	yes	yes	yes
Observation	17,181	18,893	18,893	18,893
Kleibergen-Paap rk LM statistic	31.397 [0.000]	36.023 [0.000]	36.023 [0.000]	31.397 [0.000]
Kleibergen-Paap rk Wald F-statistic	53.726 {19.93}	51.492 {19.93}	51.492 {19.93}	51.492 {19.93}
Hansen J statistic	0.6501 [0.4200]	1.2401 [0.2655]	0.3792 [0.5383]	1.0111 [0.3146]

Note: *, **, and *** denote 10%, 5%, and 1% significance levels, respectively; standard errors are in parentheses; [ ] values are p-values, and { } values are critical values at the 10% level of the Stock-Yogo weak identification test.

Source: Authors' processing.

Table 2 presents the estimation outcomes utilising the IV method. Tests conducted on the instrumental variables validate the selection process. Specifically, the Kleibergen-Paap rk LM statistic yields a p-value below 0.01, decisively rejecting the hypothesis of "insufficient identification of instrumental variables" at the 1% significance level. Furthermore, the Kleibergen-Paap rk Wald F statistic surpasses the critical value for the Stock-Yogo weak identification test at the 10% level, indicating a robust identification of instrumental variables. The Hansen J-statistic exhibits p-values exceeding 0.1, supporting the hypothesis of "exogeneity of instrumental variables". In terms of the regression coefficients, the coefficients associated with the primary explanatory variable in columns (1)-(2) remain statistically significant and positive at the 1% and 10% levels of significance, while those in columns (3)-(4) continue to lack significance. Consequently, the estimation results remain consistent with the benchmark regression outcomes, effectively addressing potential endogeneity concerns. Furthermore, to bolster the reliability of the estimation findings, we conduct additional robustness checks by substituting the

core explanatory variables, excluding firms located in specific cities, introducing new control variables, and mitigating systematic fluctuations in macroeconomic factors.

5.3 Mechanism analysis

Table 3 summarises the results of the mechanism test of digital finance affecting the amount of R&D investment and innovation in private firms. We focus on the estimated coefficients of each mediating variable and the estimated coefficients of the interaction term between digital finance and the mediating variable. From columns (1) and (4), the estimated coefficients of $Digit \times FC$ are significantly positive at the 1% and 10% levels, respectively, suggesting that financing constraints can influence the effect of digital finance on private firms' R&D investment and the number of innovations. The sum of the estimated coefficients of financing constraints and the coefficients of the interaction terms is negative, indicating that the digital economy can promote the R&D investment and innovation output of private enterprises by alleviating the corporate financing constraints. From columns (2) and (5), the estimated coefficients of $Digit \times SUB$ are both significantly positive at the 1% level, indicating that the effect of digital finance on private firms' R&D investment and innovation quantity is easily affected by government subsidies. The sum of the coefficients of SUB and the coefficient of the interaction term is positive, which indicates that digital finance can promote the R&D investment and the number of innovations of enterprises by enhancing the government's subsidy support to private enterprises. The estimated coefficient of $Digit \times MF$ in column (3) fails the significance test, while the estimated coefficient of $Digit \times MF$ in column (6) is significantly positive, indicating that the number of innovations is more sensitive to the management cost of private firms than R&D investment. In the regression equation with the number of innovations as the explanatory variable, the estimated coefficient of management cost MF is negative and the sum of its coefficients with the interaction term $Digit \times MF$ is positive, which indicates that the development of digital finance has weakened the constraints of the enterprise management cost on the innovations of the private enterprises to a certain extent. H2, H3, and H4 are verified.

Table 3. Mechanism analysis results

Variable	(1) R&D investment	(2) R&D investment	(3) R&D investment	(4) Innovation quantity	(5) Innovation quantity	(6) Innovation quantity
$Digit$	0.0109***	0.0235***	0.0028***	0.1522***	0.0936***	0.1344***
	(0.0034)	(0.0051)	(0.0004)	(0.0272)	(0.0293)	(0.0272)
FC	-0.2375***			-0.0123***		
	(0.0584)			(0.0042)		
SUB		0.0068***			0.3745***	
		(0.0016)			(0.0796)	

Variable	(1) R&D investment	(2) R&D investment	(3) R&D investment	(4) Innovation quantity	(5) Innovation quantity	(6) Innovation quantity
MF			-0.1591***			-0.3384**
			(0.0332)			(0.1338)
$Digit \times FC$	0.0445***			0.0007*		
	(0.0114)			(0.0003)		
$Digit \times SUB$		0.0015***			0.0782***	
		(0.0003)			(0.0151)	
$Digit \times MF$			0.0045			0.7308***
			(0.0061)			(0.1524)
Control variables	yes	yes	yes	yes	yes	yes
Firm	yes	yes	yes	yes	yes	yes
Year	yes	yes	yes	yes	yes	yes
Observation	16,166	16,051	16,181	16,872	16,578	16,893
R^2	0.8359	0.8369	0.8669	0.6670	0.6653	0.6670
Adjust R^2	0.8020	0.8029	0.8394	0.6025	0.5990	0.6024

Note: *, **, and *** indicate significant at the 10%, 5%, and 1% significance levels, respectively; standard errors are in parentheses.

Source: Authors' processing.

5.4 Heterogeneity discussion

First, differences in location. Given China's expansive landmass and disparate allocation of resources, substantial variations exist in economic development levels and policy landscapes across regions. To address this, we partition the sample into two subgroups: private enterprises located in coastal regions and those in inland regions based on the provinces of registration. The estimation outcomes pertaining to these sub-samples are detailed in Table 4.

Table 4. Results of subgroups based on differences in location

Variable	Private enterprises in coastal areas		Private enterprises in inland regions	
	(1) R&D investment	(2) Innovation quantity	(3) R&D investment	(4) Innovation quantity
$Digit$	0.0409***	0.0614	0.0033	0.3129**
	(0.0031)	(0.1307)	(0.0028)	(0.1598)
Control variables	yes	yes	yes	yes
Firm	yes	yes	yes	yes
Year	yes	yes	yes	yes
Observation	11462	12656	4719	7624
R^2	0.8411	0.7832	0.8121	0.7766
Adjust R^2	0.8080	0.7405	0.7735	0.7071

Note: *, **, and *** indicate 10%, 5%, and 1% significance levels, respectively; robust standard errors are in parentheses.

Source: Authors' processing.

Table 4 reveals distinct outcomes for private enterprises in coastal versus inland regions concerning the impact of digital finance on R&D investments and innovation outputs. For private enterprises in coastal areas, digital finance appears to stimulate these firms to augment their R&D expenditures. However, it falls short of significantly fostering the effective transformation of these investments into tangible innovations. In contrast, private enterprises in inland regions do not experience a substantial encouragement from digital finance to invest in R&D activities. Nevertheless, digital finance effectively boosts the number of innovation outputs from these firms. This divergence in results can be attributed to the relatively advanced and mature economic, scientific, technological, and digital finance environments in coastal regions compared to inland areas. In the coastal regions, most private enterprises already possess a high level of technological prowess and innovation capabilities. Therefore, the incentivising effect of digital finance on R&D activities is more pronounced among these enterprises. Conversely, the fierce market competition prevalent in coastal areas often constrains the impact of digital finance on private enterprises' innovation outputs, as the commercialisation opportunities may limit the realisation of significant incentivisation effects. These findings provide empirical support for H5a.

Second, there are differences in industry. Private enterprises play a pivotal role in spearheading forthcoming technological advancements and iterative innovations. The evolution of digital finance introduces novel opportunities and obstacles for high-tech private enterprises, expanding the horizons for innovation in new technological domains. Adhering to the National Bureau of Statistics GB/T4754 industry classification standards, the private enterprise sample is segregated into two cohorts: high-tech enterprises and non-high-tech enterprises. Subsequent regressions are conducted on each subgroup, with the findings detailed in Table 5.

Table 5. Results of subgroups based on differences in industry

Variable	Private enterprises in non-high-tech industry		Private enterprises in high-tech industry	
	(1) R&D investment	(2) Innovation quantity	(3) R&D investment	(4) Innovation quantity
Digit	0.0025	0.1069	0.0032***	0.2814*
	(0.0026)	(0.1412)	(0.0007)	(0.1580)
Control variables	yes	yes	yes	yes
Firm	yes	yes	yes	yes
Year	yes	yes	yes	yes
Observation	7981	9147	8290	9746
R^2	0.8542	0.8174	0.8380	0.7766
Adjust R^2	0.7951	0.7547	0.7865	0.7071

Note: *, **, and *** indicate 10%, 5%, and 1% significance levels, respectively; standard errors are in parentheses.

Source: Authors' processing.

The outcomes depicted in Table 5 unveil a noteworthy disparity in the impact of digital finance on high-tech private enterprises compared to non-high-tech private enterprises. For non-high-tech private enterprises, none of the estimated coefficients linked to digital finance exhibit statistical significance. Conversely, concerning high-tech private enterprises, the estimated coefficients associated with digital finance are notably positive and significant at the 1% and 10% levels, respectively. This suggests a pronounced innovation incentivisation effect of digital finance on high-tech private enterprises. This stronger influence on innovation among high-tech private enterprises can be attributed to the elevated technological thresholds that these enterprises encounter. Digital finance equips high-tech enterprises with an array of digital tools and technical support, facilitating their seamless utilisation and integration of these resources. Consequently, this enhances their R&D investment levels and bolsters their innovation outputs. In contrast, non-high-tech enterprises typically contend with lower technological barriers and exhibit less reliance on digital finance for innovation endeavors. As a result, the impact of digital finance on these entities is less pronounced. The testing of H5b within this context corroborates these findings, highlighting the differential impact of digital finance on innovation across high-tech and non-high-tech private enterprises.

6. Further discussions

The preceding section affirms the positive impact of digital finance on augmenting the quantity of innovations within private enterprises and stimulating R&D investment. However, a notable observation emerges: digital finance does not significantly influence the expansion of the innovation boundary or the enhancement of innovation quality within these private enterprises. This section will delve into the potential nonlinear relationship between digital finance and the innovation boundary and quality of private enterprises. Intensive investments in intangible assets at a large scale, influenced by both internal and external contexts, constitute the core of innovation within the private sector. In terms of the external environment of private enterprises, economic policies crafted by the government play a pivotal role in sculpting the external landscape for these enterprises, thereby exerting a substantial impact on the quality of their innovations and the boundaries of innovation. Economic policy uncertainty can significantly disrupt enterprises' innovation strategies, impeding their ability to accurately anticipate potential alterations in government policies. Heightened economic policy uncertainty may lead businesses to curtail non-essential investment activities, focusing instead on stabilising operations and sustaining production. Consequently, high-risk investments in innovation activities, such as expanding innovation boundaries and enhancing innovation quality, may suffer. The relationship between digital finance and private enterprise innovation quality and boundaries could exhibit nonlinear traits, influenced by the uncertainties surrounding economic policies. Turning to the internal dynamics of private enterprises, the equity structure plays a pivotal role in shaping their innovation strategies and developmental objectives. In scenarios where equity is excessively centralised, decision-making authority predominantly lies with

a subset of shareholders who may prioritise individual gains over collective prosperity. This can adversely impact minority shareholders, diminish the company's value, and impede innovative endeavours, particularly in terms of enhancing innovation quality and broadening the boundary of innovation. Conversely, an overly decentralised shareholding structure can lead to issues like suboptimal decision-making and inadequate oversight, hindering the enterprise's innovation progress. An ineffectively structured shareholding framework within private enterprises may impede their innovative capabilities. Consequently, a nonlinear correlation might exist between digital finance and the quality and boundaries of innovation within private enterprises, influenced by their equity composition.

6.1 External environmental change

The results presented in Table 6 outline the outcomes of the threshold regression test grounded in economic policy uncertainty. The analysis reveals intriguing insights into the relationship between digital finance and private enterprises' innovation quality and innovation boundaries under the influence of external economic policy uncertainty. When considering private enterprise innovation quality as the explanatory variable, the Bootstrap sampling results align significantly with the singlethreshold hypothesis, indicating a clear threshold for the impact of digital finance on the innovation quality of these enterprises. Conversely, the test outcomes under the double threshold hypothesis do not exhibit significance, suggesting the presence of a single discernible threshold effect.

Shifting the focus to the innovation boundary as the explanatory variable, the results showcase significant findings for both the single-threshold hypothesis and the double-threshold hypothesis. However, the test outcomes under the triple-threshold hypothesis do not reach significance. This points towards the existence of two significant thresholds governing the impact of digital finance on the innovation boundary of private enterprises. Consequently, it becomes evident that within the realm of economic policy uncertainty's external environment, a certain nonlinear correlation emerges between digital finance and the innovation quality as well as the innovation boundary of private enterprises. This underscores the intricate and nuanced relationship shaped by the interplay between digital finance, economic policy uncertainty, and the innovative dynamics within private enterprises.

Table 6. Model selection and threshold values based on economic policy uncertainty

Explained variable	Model	Threshold value	F-value	P-value	Bootstrap times	Critical value		
						1%	5%	10%
Inno2	Single	363.8860	71.32	0.000	500	15.493	11.812	7.647
	Double	none	0.59	1.000	500	14.924	9.397	7.308
Inno3	Single	460.7814	46.03	0.000	500	13.221	9.246	8.506
	Double	364.0261	11.67	0.000	500	10.447	8.546	6.711
		460.7814						
	Triple	none	4.57	0.660	500	14.107	13.996	11.623

Source: Authors' processing.

In Table 7, the threshold regression estimates based on economic policy uncertainty are summarised. Regarding the influence of digital finance on innovation quality, when economic policy uncertainty falls below 363.8860, the estimated coefficient for digital finance stands at 0.3420, significant at the 1% level. Conversely, with economic policy uncertainty surpassing 363.8860, the estimated coefficient for digital finance becomes negative and statistically insignificant. These findings suggest that digital finance can indeed incentivise private enterprises to enhance innovation quality solely under conditions of low economic policy uncertainty. In terms of digital finance's impact on the innovation boundary, when economic policy uncertainty remains under 364.0261, the positive effect of digital finance on the innovation boundary, proves significant. Within the range of 364.0261 to 460.7814, the positive effect persists but diminishes in strength (from 0.1165 to 0.0659). Once economic policy uncertainty exceeds 460.7814, the effect of digital finance on firms' innovation boundaries transitions from positive promotion to negative inhibition. This outcome suggests that increased economic policy uncertainty gradually attenuates the enabling impact of digital finance on private enterprises to expand their innovation boundaries, eventually leading to a certain inhibitory effect. This phenomenon may arise from the tendency of high economic policy uncertainty to disrupt and distort the innovation decisions of private enterprises, steering them towards less risky investment projects or the retention of precautionary funds to ensure stability. Such tendencies are counterproductive to enhancing innovation quality and broadening the innovation boundaries of private enterprises (Phan et al., 2019).

Table 7. Threshold regression estimates based on economic policy uncertainty

		Innovation quality	Innovation boundary
Digit	Low	0.3420***(0.0518)	0.1165**(0.0458)
	Middle		0.0659***(0.0091)
	High	-0.0576 (0.0529)	-0.0783***(0.0082)
Percentage of samples in low range (%)		39.98%	40.66%
Percentage of samples in high range (%)		61.02%	34.91%
Control variable		yes	yes
Observation		19,754	19,754

Note: *, **, and *** indicate significant at the 10%, 5%, and 1% significance levels, respectively; standard errors are in parentheses.

Source: Authors' processing.

6.2 Internal environmental change

Table 8 presents the outcomes of the threshold regression analysis centered on enterprises' equity concentration. The findings reveal that under either innovation quality or innovation boundary as the explained variable, the Bootstrap sampling outcomes align significantly with the single-threshold hypothesis at a 1% significance level. However, the results derived from the double-threshold

hypothesis lack significance, suggesting the presence of a sole threshold value within the model. Influenced by the internal environmental change (equity concentration), the effects of digital finance on both innovation quality and innovation boundary of private firms exhibit distinct nonlinear attributes. This underscores that the impact of digital finance on private enterprises' innovation dynamics is intricately shaped by the concentration of equity within these organisations, manifesting in a discernible single threshold rather than multiple thresholds.

Table 8. Model selection and threshold values based on equity concentration

Explained variable	Model	Threshold value	F-value	P-value	Bootstrap times	Critical value		
						1%	5%	10%
Inno2	Single	22.0700	10.17	0.020	500	12.805	8.614	8.046
	Double	none	3.62	0.800	500	11.347	10.879	10.181
Inno3	Single	56.0000	12.67	0.000	500	17.463	15.638	13.524
	Double	none	4.36	0.520	500	15.158	11.890	9.985

Source: Authors' processing.

Table 9 compiles the regression findings utilising enterprise equity concentration as the threshold variable. Concerning the influence of digital finance on enterprise innovation quality, an estimated coefficient of 0.3432 is observed, with significance at the 1% level when the equity concentration falls below 22.07%. Conversely, when equity concentration exceeds 22.07%, the estimated coefficient for digital finance becomes negative and statistically insignificant, indicating that digital finance can effectively stimulate innovation quality solely under conditions of lower equity concentration within private enterprises. Contrastingly, the impact of digital finance on the innovation boundary of private enterprises is pronounced only in situations of high equity concentration. Specifically, when equity concentration remains below 56%, the estimated coefficient for digital finance is positive, but insignificant. However, when the equity concentration surpasses 56%, the estimated coefficient is 0.0294 and is significant at the 1% level. Organisations with elevated equity concentration typically demonstrate heightened decision-making capabilities and operational efficiency, attributes that fortify the incentivising effect of digital finance on expanding innovation boundaries.

Table 9. Threshold regression estimates based on equity concentration

		Innovation quality	Innovation boundary
Digit	Low	0.3432***(0.0487)	0.0199 (0.0149)
	High	-0.0087 (0.0378)	0.0294*(0.0155)
Percentage of samples in low range (%)		36.81%	93.49%
Percentage of samples in high range (%)		63.19%	6.51%
Control variable		yes	yes
Observation		18,870	18,870

Note: *, **, and *** indicate significant at the 10%, 5%, and 1% significance levels, respectively; standard errors are in parentheses.

Source: Authors' processing.

7. Conclusions

This study focuses on Chinese A-share listed private enterprises in Shanghai and Shenzhen from 2011 to 2021, investigating the influence of digital finance on private enterprise innovation empirically. It delves into the mechanisms through which digital finance impacts innovation and assesses potential heterogeneity effects. The research explores potential non-linear relationships between digital finance and innovation quality, as well as innovation boundaries of private enterprises, considering both external and internal enterprise environments. The study reveals that digital finance serves as a significant driver of innovation within private enterprises. It highlights that digital finance encourages increased R&D investments and boosts innovation quantity. This is achieved through three pathways: easing financial constraints, enhancing access to subsidies, and reducing operational costs for enterprises. In comparison to private enterprises in coastal regions and non-high-tech sectors, digital finance demonstrates a stronger motivating effect on innovation among private enterprises in inland regions and high-tech industries. The study suggests that deeper digital finance integration and higher digitisation levels benefit private enterprises in augmenting R&D investments and innovation quantities. Additionally, broader digital finance coverage notably enhances the innovation output of private enterprises. Under the influence of external factors (such as economic policy uncertainty) and internal dynamics (like enterprise equity concentration), digital finance's impact on private enterprise innovation quality and boundaries exhibits non-linear tendencies, displaying a discernible "threshold effect." Lower levels of economic policy uncertainty are conducive to digital finance that improves innovation quality and expands innovation boundaries within private firms. Conversely, heightened economic policy uncertainty gradually diminishes digital finance's role in widening innovation boundaries, potentially even impeding innovation. In environments characterised by low equity concentration, digital finance can effectively drive innovation quality, whereas in high equity concentration settings, it stimulates innovation boundary expansion.

This study opens several avenues for future research. Future research should validate these findings by analysing different stages within the 2011–2021 timeframe. Through comparing the epochs devoid of COVID-19 (prior to 2019) with those during the prevalence of COVID-19 (subsequent to 2019), it becomes possible to unearth differential influences and thereby offer profound insights into the intricate relationship between digital finance and private enterprise innovation within the context of China.

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