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Does FinTech development facilitate firms' innovation? Evidence from China

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ABSTRACT

This study examines the impact of financial technology (FinTech) development on firms' innovation. Using Chinese listed firms' panel data from 2011 to 2021 and the FinTech indicators we constructed, we find that FinTech development significantly facilitates firms' innovation by alleviating their information asymmetry and financing constraints. This finding continues to hold after a series of robustness tests and endogeneity discussions. Moreover, we find that the effect of FinTech development on innovation is more pronounced for non-state-owned firms, firms in the central region, and high-tech firms. These results offer important policy implications as they demonstrate the crucial role of FinTech in the high-quality development of the real economy.

1. Introduction

Ever since Solow (1956) first argued that technological innovation fosters economic growth, much research has investigated the role of endogenous technological progress in economic growth. It is widely recognized that technological innovation is the key to driving persistent economic growth (Grossman & Helpman, 1994; Lucas Jr, 1988; Romer, 1990). Furthermore, recent literature suggests that innovation can also contribute to firm survival (Eisdorfer & Hsu, 2011), competitive advantage (Porter, 1992), and firm performance (Calantone, Cavusgil, & Zhao, 2002; Yalcinkaya, Calantone, & Griffith, 2007), as innovating firms are more likely to benefit from spillovers and are less likely to be affected by negative macroeconomic events (Geroski, Machin, & Van Reenen, 1993). For this reason, governments have attached great importance to technological progress and implemented a series of measures, such as financial subsidies and tax incentives, to encourage companies to conduct innovation programs.

However, it is obvious that firms remain under-innovative in the real economy. As innovation activities require large and continuous capital investment that cannot fully be resourced through internal financing, it is important to obtain external financing for R&D projects (Hall, 2002). Compared with general projects, innovation projects have long R&D cycles, high output uncertainty, fewer tangible collateral, and high levels of information asymmetry, and are thus high-risk investments for financial institutions (Holmstrom, 1989; Kothari, Laguerre, & Leone, 2002). In consequence, innovative firms always face serious financing constraints and high financing costs (Hall & Lerner, 2010) that significantly limit their innovation (Bronzini & Piselli, 2016; Guariglia & Liu, 2014). Therefore, it is crucial to explore new types of financial products and services to provide better financial support for innovation.

In recent years, financial institutions have increasingly started using big data, artificial intelligence, blockchain, cloud computing, and other emerging technologies to improve financial services, leading to the rapid development of financial technology (FinTech). According to KPMG (2021), global FinTech investment reached $210 billion by 2021, up 147% from 2020. The Asia Pacific region invested $27.5 billion, of which Chinese companies invested $2.63 billion. By December 2021, there were a total of 183,511 FinTech companies registered in China (as shown in Fig. 1), of which 36,082 were newly registered—an increase of 28.08% from the previous year. Meanwhile, the Chinese government has placed a high value on FinTech development. In 2022, The People's Bank of China issued the "Financial Technology Development Plan (2022-2025)", which makes explicit arrangements for FinTech development. FinTech development has greatly increased the scale, expanded the scope and improved the efficiency of financial service, (Li, Lin, & Xu, 2020; Ozili, 2018), allowing us to conclude that it would definitely provide a better financial environment for firm innovation.

In this paper, we empirically investigate the impact of FinTech

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development on firms' innovation in a time of continuous technology breakthrough. Using panel data on Chinese listed firms in the A-share market from 2011 to 2021 and the prefecture-level FinTech indicator measured by the number of newly registered FinTech companies, we find that FinTech development can reduce firms' information asymmetry and alleviate firms' financing constraints, thereby enhancing their innovation capacity. Specifically, firms' R&D input, patent output and innovation efficiency can all be significantly improved due to FinTech development. Furthermore, we find that the effect of FinTech development on firms' innovation varies among firms with different property rights, in different geographical locations and with different technological attributes.

We contribute to the literature in several ways. First, we complement the research on FinTech development and firm innovation. A large body of literature investigates the micro effect of FinTech development, including its effect on firms' financial structure (Feng, Zhang, & Li, 2022; Lai, Yue, Guo, & Zhang, 2023), stock returns (Chen, Wu, & Yang, 2019; Wang, Cao, Feng, Lu, & Shan, 2023), and financial performance (Hanelt, Firk, Hildebrandt, & Kolbe, 2021; Lin, Yip, Ho, & Sambasivan, 2020). However, few studies focus on the relationship between FinTech development and firm innovation (Ding, Gu, & Peng, 2022; Hui, Zhao, Liu, & Li, 2023). Our research extends the relevant literature and reveals both the role of FinTech development in enhancing firms' innovation and the mechanism by which it does so.

Second, regarding the measurement of firms' innovation, most of the current literature only explores the single dimension of input or output. Because innovation is a complex process with several stages ranging from basic research to the penetration of the market with new products (Hollenstein, 1996), it is necessary to consider a broad range of innovation indicators to distinguish the input and output of innovation activities (Rogers & Rogers, 1998; Wan, Ong, & Lee, 2005). In this paper, we provide a perspective that includes three dimensions of innovation, namely R&D input, patent output and innovation efficiency, in the same framework, thus generating a more comprehensive evaluation on the relationship between FinTech development and firms' innovation.

Third, we construct a prefecture-level FinTech indicator by using the exact number of newly registered FinTech companies in China. Most previous studies measure FinTech development with a text mining approach (Chen et al., 2019; Li, Wu, & Xiao, 2020), that is, designating the number of relevant keywords' occurrences on the Internet as a FinTech proxy. However, this method is likely to suffer from lexicon selection bias and news recurrence, thus causing significant measurement error. The approach we adopt is based on exact FinTech company information, so it can avoid the above problems and thus provide a more objective and accurate prefecture-level FinTech indicator.

The remainder of this paper is organized as follows. Section 2 provides a review of the relevant literature and provides the research hypotheses. Section 3 includes the methods, variables and data sources used in the empirical analysis. Section 4 presents and discusses the empirical results. Finally, Section 5 describes the study's conclusions and provides several policy implications.

2. Research hypothesis

2.1. The impact of FinTech development on firms' innovation

A large body of literature shows that inadequate external financing is the main reason for the low level of innovation in firms (Brown, Fazzari, & Petersen, 2009; Hall, 2002). Based on this finding, scholars have explored extensively the factors that could mitigate firms' financing constraints and stimulate firms' innovation. Some researchers have found that financial development and financial deepening enable firms to have easier and cheaper access to external finance, and thus significantly enhance their innovation (Ayyagari, Demirgüç-Kunt, & Maksimovic, 2011; Hsu, Tian, & Xu, 2014). Following this mainstream idea, we first develop our basic hypothesis by discussing the impact of FinTech development on firms' innovation.

According to the Financial Stability Board (FSB), FinTech enables the financial industry to use artificial intelligence, big data, blockchain and other advanced technologies to improve products and services, creating the possibility for substantial financial development. Specifically, it does so in three ways. First, FinTech can expand financial services in terms of scope and space, as it enables financial institutions to reach places that are too geographically remote to have physical financial service outlets, and to become involved in projects whose risk and value are too complex to be accurately identified by traditional financial technics. Second, FinTech can decrease financial costs by improving financial institutions' ability to process risk information and the efficiency of their ex-post monitoring (Sheng, 2021; Wang et al., 2023). In some specific scenarios, FinTech can even avoid financial intermediation costs by providing direct platforms for borrowers and lenders. Third, FinTech development can improve the efficiency of financial services (Claessens & Laeven, 2005), as it enables users to perform multiple online transactions worldwide simply by downloading mobile applications while avoiding excessive paperwork and unnecessary processes (Bajunaied, Hussin, & Kamarudin, 2023; Lee, Li, Yu, & Zhao, 2021).

Based on the above analysis, we strongly believe that FinTech development can significantly boost the financial industry by optimizing

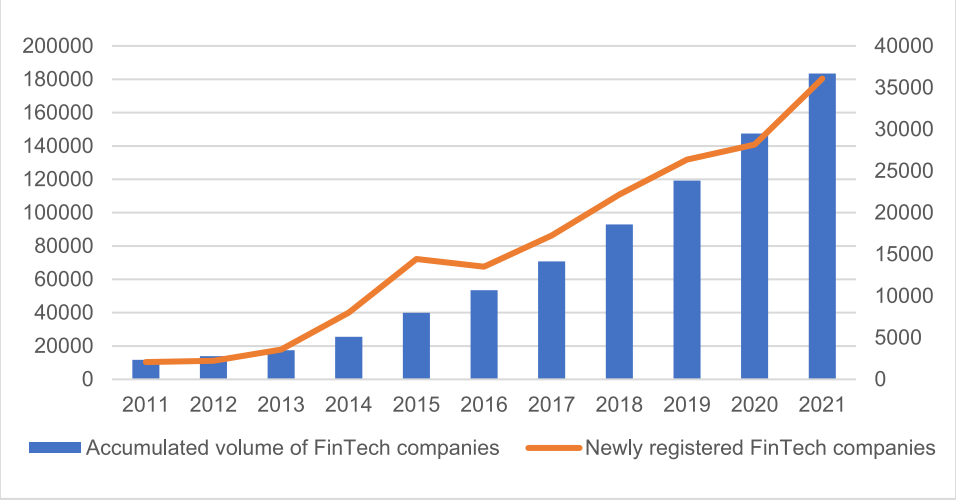

Fig. 1. The number of FinTech companies registered in China.

the supply of financial products and services, thus positively influencing firms' innovation. Therefore, we propose the following hypothesis:

Hypothesis 1. FinTech development has a positive impact on firms' innovation.

2.2. FinTech development, information asymmetry and firms' innovation

Information asymmetry is prevalent between firms and external investors, especially for R&D-intensive firms, where the secrecy and uncertainty surrounding innovation activities make the information asymmetry particularly severe (Anton & Yao, 2002). According to the relevant literature, information asymmetry not only increases firms' financing constraints (Fazzari, Hubbard, & Petersen, 1988; Kaplan & Zingales, 1997) but also causes moral hazard (Guariglia & Liu, 2014; Hirshleifer, 1993), thus posing a serious obstacle to firms' innovation. Hence, we infer that reduced information asymmetry would promote firms' innovation.

FinTech development enables traditional financial institutions to make full use of cutting-edge technologies to obtain firms' information on production operations, thus effectively relieving information asymmetry (Sedunov, 2017; Sheng, 2021). This effect is mainly manifested in the following three aspects: 1) FinTech enables financial institutions to use technology to collect key information on firms' innovation projects that firms are usually reluctant to disclose. 2) FinTech enables financial institutions to have greater access to complementary information by capturing firms' unstructured data (e.g., images, videos and audio) from multiple sources and performing structured transformations on it (Wang et al., 2023). 3) FinTech can increase the transparency of management operations, thus mitigating moral hazard and avoiding management laziness and negligence in R&D activities.

Therefore, we conclude that information asymmetry is a plausible channel between FinTech development and firms' innovation, and we then propose the following hypothesis:

Hypothesis 2. FinTech development enhances firms' innovation by alleviating information asymmetry between firms and external investors.

2.3. FinTech development, financing constraints and firms' innovation

In general, innovation activities have great financial needs that cannot be adequately supported by internal financing alone, meaning that significant external financing is necessary (Hall, 2002). However, R&D-intensive firms, which have a high level of information asymmetry and lack tangible assets as collateral, suffer greatly from serious credit discrimination in traditional credit markets (Berger & Udell, 1990; Opler & Titman, 1994). Firms in China, in particular, often face more severe financing constraints owing to the under-development of China's capital market and the predominance of bank credit.

According to Fazzari et al. (1988), a higher degree of financing constraints could lead to a shortfall in firms' cash flows, forcing firms to reduce their investment. In this case, even promising innovation projects are likely to be shut down due to firms' preference for tangible assets over intangible assets (Baldwin & Okubo, 2006). Therefore, it is widely recognized in the literature that financing constraints are a major impediment to firms' innovation (Brown et al., 2009; Hall, 2002). In other words, having fewer financing constraints promotes higher innovation capacity.

The development of FinTech can reduce firms' financing constraints in two ways: by expanding the traditional credit supply, and by increasing credit supply from new platforms. The first works by alleviating information asymmetry. As we explained earlier, FinTech enables financial institutions to precisely track firms' production, operation, and other relevant data, thus effectively limiting information asymmetry. With sufficient information, financial institutions have a better understanding of firms' risk and long-term value (Porter, 1992), thus leading to more credit supply and less risk premium (Biddle, Hilary, & Verdi, 2009), substantially reducing firms' financing constraints. The second works by facilitating alternative platforms that directly link supply with demand, such as P2P, crowdfunding, and big data credit platforms. These platforms provide diversified financial products and services to firms that may have limited ability to raise funds in a traditional credit market (Bollaert, Lopez-de-Silanes, & Schwienbacher, 2021). As a result, these alternative funding sources enhanced by FinTech can further mitigate firms' financing constraints.

Therefore, we conclude that FinTech development can effectively mitigate firms' financing constraints and thus promote firms' innovation. We thus propose the following hypothesis:

Hypothesis 3. FinTech development enhances firms' innovation by mitigating firms' financing constraints.

3. Data, variables and model

3.1. Data

We compile data from three sources: 1) the China Stock Market & Accounting Research database (CSMAR), from which we retrieve the financial data and R&D expenditure of Chinese listed firms; 2) the Chinese Research Data Services (CNRDS), from which we obtain listed firms' patent data; and 3) the website of "Tianyancha", from which we get the business registration information concerning FinTech companies that we use to construct the prefecture-level FinTech indicator.

We begin with all the firms listed in the China A-Share Market and apply the following sample selection process. First, as the asset and liability functions of financial institutions differ to those of general firms, we omit financial firms such as banks and insurance companies. Second, on the basis that firms listed as special treatment (ST & *ST) display abnormal financial performance, we exclude the firms so labelled during the sample period. Third, to avoid the impact of firms' abnormal financial performance, we further remove the firms that experienced insolvency in the sample period. Fourth, we omit observations with missing data on key variables, for the sake of sample completeness and the accuracy of the estimation results. In addition, to relieve the impact of outliers, all continuous variables are winsorized at the 1st and 99th percentile levels of their empirical distribution. Our final sample includes 22,433 observations of 3620 firms from 2011 to 2021.

3.2. Variables

3.2.1. Dependent variable: firms' innovation

To comprehensively examine the impact of FinTech development on the whole process of firms' innovation, we adopt innovation input, innovation output and innovation efficiency as the three proxies for firms' innovation. Innovation input is measured as the logarithm of R&D expenditure. For innovation output, the relevant literature mainly adopts applied patents or granted patents as a measure. Since application is closer to firms' actual capacity (Du, Li, & Yan, 2019), we take the logarithm [1+ the number of applied patents] as our output proxy. Finally, we measure innovation efficiency, which reflects firms' ability to convert input into output, by taking the ratio of the logarithm [1+ number of applied patents] to the logarithm of R&D expenditure.

3.2.2. Independent variable: FinTech development

We obtain the registration information of related FinTech companies by searching for keywords on the website "Tianyancha", and then construct the prefecture-level FinTech indicator using the number of newly registered FinTech companies.

FinTech is defined as a new financial industry that applies cutting-edge technology to improve financial services. This technology includes artificial intelligence, blockchain, cloud computing, and big data. In China, FinTech most commonly operates in cooperation with

financial institutions and FinTech companies, so we consider using the prefecture-level intensity of FinTech companies a reliable measurement of FinTech development (Song, Zhou, & Si, 2021).

Following Song et al. (2021), we first search for "financial technology", "artificial intelligence", "blockchain", "cloud computing", "big data", and other keywords shown in company names or business scope on the "Tianyancha" website to obtain the registration information of relevant companies. Second, we discard companies that have been operating for less than one year and that demonstrate operating abnormalities—such as having ceased operations, or been dissolved or suspended—to alleviate the impact of "shell company" registration on the accuracy of FinTech development indicators. Third, the definition of FinTech requires the relevant companies to use technology to enhance financial services. Hence, we further filter the previously obtained company information by searching for "finance", "insurance", "credit", "clearing", "payment" and other keywords related to financial business, matching these with the business scope of the companies, and then keeping the matched samples. Finally, we collect the number of newly registered FinTech companies each year on the prefecture level, and then take the logarithm of the value to indicate the FinTech development level, with higher values meaning better FinTech development.

3.2.3. Controls

First, we include the following firm-level indicators to control the influence of firms' own factors on innovation. Size is controlled for on the basis that larger firms tend to have higher innovation capacity (Acs & Audretsch, 1988), and we take the logarithm of the book value of their total assets to measure their size. Age is used to reflect the fact that firms in different stages of their lifecycle have different innovation potential (Coad, Segarra, & Teruel, 2016), and we use the number of years from a firm' s listed date to measure its age. Leverage is the ratio of debt to the book value of assets, which is used to control the impact of firms' financial structure on their innovation capability. Return on assets (ROA) is the ratio of operating income before depreciation of the book value of total assets, which is used to reflect the impact of firms' profitability on innovation. Growth is measured as the growth rate of operating income to control the impact of the firms' business development on their innovation capacity. Cashflow is the ratio of net cash flows from operating activities to the book value of total assets at the end of the year, and is used to control the impact of liquidity. Employee is the logarithm of [1+ the total number of employees at the end of the year], which is also relevant to firms' innovation capacity. Top1 is measured as the shareholding of a firm's largest shareholder, to control the impact of board decisions on the layout of firms' innovation. Management is the percentage of management shareholding, which reflects management's planning and decisions for firms' continuous innovation.

Second, we include some prefecture-level macro variables that reflect the impact of regional development on firms' innovation. Given that cities with higher levels of economic development have better resources and greater ability to attract talent, and cities with better development of the financial sector can boost more efficient financing activities, we control provinces' economic development (EconDev), financial development (FinDev) and population growth (Population) in our model. Specifically, EconDev refers to the GDP growth rate, FinDev represents the ratio of financial sector output to GDP, and Population refers to the population growth rate.

3.3. Empirical model

To investigate the impact of FinTech development on firms' innovation, we set up our econometric model as follows:

$$Innov_{it} = \alpha + \beta_0 FinTech_{it} + \beta_1 X_{it} + \sum Year + \sum Industry + \sum Province + \varepsilon_{it} \quad (1)$$

where i and t stand for firm i and year t respectively, and $Innov_{it}$ represents $LnRD_{it}$, $Lnpatent_{it}$, or Eff_{it}, which are the three measures we use to indicate firms' innovation. $FinTech_{it}$ is the core explanatory variable, which captures the prefecture-level FinTech development. X_{it} refers to a set of controls that we mentioned before. $\sum Year$ stands for the time fixed effect for which we control, $\sum Industry$ is the industrial fixed effect, and $\sum Province$ refers to the province fixed effect. Since firms in the same industry have similar production and process techniques, which enable other firms to imitate or copy an innovating firm's patented technology, we control for the industrial fixed effect rather than firm fixed effect. We also choose to control for the fixed effect for province rather than for city because the innovation environment and policy preferences usually do not vary much within a province. ε_{it} is disturbance term. The variables' definitions are listed in Table 1.

4. Empirical results

4.1. Descriptive statistics

Table 2 reports the descriptive statistics for the variables used in our regressions. The maximum and minimum values of LnRD are 21.9558 and 13.8365, respectively, which suggests that there are significant differences among firms' R&D expenditure. Lnpatent takes values between 7.1732 and 0, revealing that there are several sample firms that do not have innovation output. The maximum and minimum values of Eff are 0.3280 and 0, respectively, with a standard deviation of 0.0774, which shows that there are great differences of innovation efficiency among sample firms. The descriptive statistics of the three dependent

Table 1
Definition of variables.

Type of variable	Variable Name	Definition	Measurement
Dependent variable	LnRD	R&D input	Log [R&D expenditure]
	Lnpatent	Patent output	Log [1+ the number of applied patents]
	Eff	Innovation efficiency	Log [1+ the number of applied patents] / Log [R&D expenditure]
Core independent variable	FinTech	FinTech development	Log [1+ the number of FinTech firms at prefecture-level]
Control Variables	Size	Firm size	Log [total assets]
	Age	Firm Age	Year of the sample period -Year of the firm listing
	Leverage	Financial leverage	Total debts / Total assets
	ROA	Return on assets	Income before interest and tax / Total assets
	Growth	Firms' growth rate	The growth rate of operating income
	Cashflow	Cashflow rate	Cash flow from operations / Total assets
	Employee	The total number of employees	Log [1+ the number of employees in service at the end of the year]
	Top1	The shareholding of the firm's largest shareholder	The shareholding of the firm's largest shareholder
	Management	The shareholding of the firm's management	The shareholding of the firm's management
	EconDev	Economic development	GDP growth rate of the province
	FinDev	Financial development	The financial sector output / GDP of the province
	Population	Population growth	Population growth rate of the province

Note: This table provides the definitions of the variables used in our regressions.

Table 2
Descriptive statistics of the variables.

Variables	Mean	SD	Min	Max
LnRD	17.9309	1.4593	13.8365	21.9558
Lnpatent	3.1161	1.5816	0.0000	7.1732
Eff	0.1593	0.0774	0.0000	0.3280
FinTech	4.8664	1.9315	0.6931	7.9445
Size	22.1448	1.2965	20.0206	26.3308
Age	8.3739	7.2100	0.0000	26.0000
Lev	0.3856	0.1931	0.0491	0.8351
ROA	0.0455	0.0552	−0.1928	0.1976
Growth	0.1716	0.3319	−0.4601	1.8333
Cashflow	0.0503	0.0634	−0.1249	0.2305
Employee	7.7040	1.2158	5.2933	11.2830
Top1	33.9887	14.5859	8.4100	73.6700
Management	17.5247	21.0764	0.0000	69.0639
EconDev	0.0865	0.0447	−0.0824	0.2022
FinDev	0.0878	0.0422	0.0326	0.1991
Population	0.0075	0.0096	−0.0212	0.0406

Note: This table provides the summary statistics for the variables used in the baseline regression.

variables reveal that the innovation capacity varies greatly among different firms. Meanwhile, the independent variable FinTech takes values between 7.9445 and 0.6931, with a standard deviation of 1.9315, indicating that FinTech development shows great variation among different prefectural cities in China. The distributions of the other control variables are similar to those shown in the previous literature (Lin et al., 2020; Yu, Wu, Zhang, Chen, & Zhao, 2021).

4.2. Baseline estimation

Table 3 reports the results of our baseline estimation, in which we use LnRD, Lnpatent, and Eff as proxies for firms' innovation. We first conduct a basic regression without adding control variables to examine the impact of FinTech development on firms' innovation, with the results displayed in columns (1)–(3). In columns (1)–(3), we include our key independent variable FinTech with year, industry and province fixed effects. To be consistent with FinTech's dimensionality, standard errors are clustered at the prefecture-level, which is statistically reasonable. The results show that the coefficients of FinTech are all positive and significant at the 1% level, indicating that FinTech development can facilitate firms' innovation and play a catalytic role in three areas: R&D input, patent output and innovation efficiency. In columns (2)–(6), we add controls in regression according to Eq. (1), and the coefficients of FinTech are still all positive and significant at the 1% level. Therefore, we prove that FinTech development can enhance firms' innovation capacity.

4.3. Channel analysis

In this section, we analyze two potential channels through which FinTech development affects firms' innovation. The first is information asymmetry and the second is financing constraints, both of which have been proved to be highly relevant to firms' innovation capacity.

4.3.1. Channel analysis of information asymmetry

To test the first channel, we apply a two-step regression approach (Duan, El Ghoul, Guedhami, Li, & Li, 2021; Griffin, Guedhami, Li, & Lu, 2021). In the first step, we investigate the impact of FinTech on the level of firms' information asymmetry (ASY). In the second step, we examine the impact of the predicted ASY value on three proxies of firms' innovation. The regression equation for testing channel 1 is as follows:

Table 3
Basic results: effect of FinTech development on firms' innovation.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	LnRD	Lnpatent	Eff	LnRD	Lnpatent	Eff
FinTech	0.0408***	0.0552***	0.0027***	0.0352***	0.0503***	0.0025***
	(0.0130)	(0.0151)	(0.0008)	(0.0110)	(0.0147)	(0.0008)
Size				0.5918***	0.4551***	0.0184***
				(0.0264)	(0.0263)	(0.0013)
Age				−0.0057**	0.0040	0.0002
				(0.0026)	(0.0033)	(0.0002)
Lev				−0.3721***	−0.2548**	−0.0101**
				(0.0979)	(0.0984)	(0.0050)
ROA				1.2072***	0.9941***	0.0446***
				(0.2114)	(0.2471)	(0.0131)
Growth				0.0703***	−0.0354	−0.0020
				(0.0227)	(0.0304)	(0.0018)
Cashflow				0.6116***	−0.4411**	−0.0328***
				(0.1599)	(0.1986)	(0.0107)
Employee				0.3368***	0.3530***	0.0160***
				(0.0261)	(0.0288)	(0.0015)
Top1				−0.0022**	−0.0011	−0.0001
				(0.0009)	(0.0015)	(0.0001)
Management				−0.0001	0.0023**	0.0001**
				(0.0006)	(0.0010)	(0.0001)
EconDev				0.1414	0.2257	0.0130
				(0.1477)	(0.2408)	(0.0132)
FinDev				2.3750**	2.9568*	0.1438*
				(0.9497)	(1.5051)	(0.0808)
Population				0.7942	4.2285**	0.2404**
				(1.1316)	(1.7633)	(0.0969)
_cons	17.7326***	2.8475***	0.1577***	2.0388***	−10.1810***	−0.3847***
	(0.0675)	(0.0816)	(0.0041)	(0.4284)	(0.4518)	(0.0228)
Year	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.2403	0.2374	0.2361	0.6668	0.5103	0.4311
N	22,433	22,433	22,433	19,186	19,186	19,186

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

$$Innov_{it} = \alpha + \gamma_0 \widehat{ASY}_{it} + \gamma_1 X_{it} + \sum Year + \sum Industry + \sum Province + \varepsilon_{it} \quad (2)$$

where $Innov_{it}$ represents firms' innovation (which are the same three proxies we use in Eq. (1), i.e., LnRD, Lnpatent and Eff). $\widehat{ASY}_{it}$ is the predicted value generated from the first-step regression. Following the literature that uses individual stock trading information to capture the degree of information asymmetry between uninformed and informed traders (Bharath, Pasquariello, & Wu, 2009; Song et al., 2021; Yu et al., 2021), we calculate the liquidity ratio, the illiquidity ratio and the reversal coefficient, and then extract the first principal component of the three indicators as a proxy for information asymmetry. The higher the value of this indicator, the greater the information asymmetry.

Table 4 reports the results of the test of information asymmetry channel. Column (1) provides the result of the first-step regression, which shows that the regression coefficient of FinTech is negative and significant. It suggests that the development of FinTech can reduce the level of information asymmetry between firms and external investors, which is reasonable since FinTech enables financial institutions to have increased access to firms' information (Kshetri, 2016; Sheng, 2021).

Columns (2)–(4) provide the results of the second-step regression. We notice that the effect of the predicted ASY value is entirely negative and significant, which means that information asymmetry inhibits the enhancement of firms' innovation capacity. This is because financial institutions with full information are going to lend more funds to firms with promising innovation projects (Feng et al., 2022; Li, Yan, Song, & Yang, 2020), which would then lead to significant elevation of firms' innovation (Gomber, Kauffman, Parker, & Weber, 2018). The above results indicate that the development of FinTech could reduce the level of information asymmetry between firms and external investors, in turn promoting firms' innovation.

4.3.2. Channel analysis of financing constraints

To test the financing constraints (FC) channel, we also adopt the two-step regression approach. In the first step, we regress FC on FinTech and other controls in Eq. (1). In the second step, we examine the impact of the predicted FC value on firms' innovation. The regression equation used for testing the channel is as follows:

$$Innov_{it} = \alpha + \gamma_0 \widehat{FC}_{it} + \gamma_1 X_{it} + \sum Year + \sum Industry + \sum Province + \varepsilon_{it} \quad (3)$$

where $Innov_{it}$ is firms' innovation, which coordinates with the measurement in Eq. (1); FC refers to firms' financing constraints; and $\widehat{FC}_{it}$ is the predicted value generated from the first-step regression. It has been recognized in the literature that the SA index proposed by Hadlock and Pierce (2010) is a reliable measure for Chinese firms' financing constraints (Li, Wu, & Xiao, 2020; Lu & Chen, 2017). Thus, we collect the SA index from CSMAR database to reflect firms' financing constraints. The value of the SA index is negative, with higher absolute values meaning more severe financing constraints. For a more intuitive understanding of the empirical results, we take the absolute value of SA index as FC, with higher FC indicating more severe financing constraints.

Table 5 provides the results of testing the financing constraints channel. Column (1) shows the results of the first-step regression. We find that the regression coefficient of FinTech in column (1) is negative and significant at the 5% level, indicating that the development of FinTech can reduce the level of firms' financing constraints (Ding et al., 2022; Feng et al., 2022). Columns (2)–(4) refer to the results of the second-step regression, showing that the regression coefficients of $\widehat{FC}_{it}$ are all negative and statistically significant. This implies that the more severe firms' financing constraints are, the less innovative the firms, which is consistent with previous literature (Brown et al., 2009; Guariglia & Liu, 2014). Since firms with severe financing constraints are more likely to allocate funds to short-term productive investment instead of innovation projects, their innovation capacity is always greatly inhibited by financing constraints (Brown et al., 2009; Hall, 2002). Therefore, combining the results of the two-stage regression, we find that the development of FinTech can alleviate firms' financing constraints, which in turn enhances firms' innovation capacity.

4.4. Heterogeneity analysis

4.4.1. Heterogeneous impact on firms with different ownership

The coexistence of state-owned and non-state-owned firms is a unique feature of China's economic system, making it necessary to investigate the heterogeneous impacts of FinTech development on firms' innovation under different arrangements of property rights. Therefore, we divide the sample firms into state-owned and non-state-owned groups based on the firms' controllers, and then run group regressions.

The results are presented in Table 6. The results show that in the subsample of state-owned firms, the development of FinTech does not significantly affect firms' R&D investment, but significantly improves the level of patent output and firms' innovation efficiency. In the subsample of non-state-owned firms, we find that the development of FinTech not only increases firms' R&D investment, but also improves their patent output and innovation efficiency. An overall perspective suggests that the effect of FinTech development on innovation is more pronounced for non-stated-owned firms.

The results can be interpreted in the following way. On the one hand, with the endorsement of government's credit, state-owned firms usually have priority in obtaining external funding in China's special financial system, which is dominated by state-owned banks, and have easier

Table 4
Channel 1: information asymmetry.

Variables	(1)	(2)	(3)	(4)
	ASY	LnRD	Lnpatent	Eff
FinTech	−0.0036**			
	(0.0017)			
$\widehat{ASY}$		−9.8695***	−14.1121***	−0.6911***
		(3.0780)	(4.1239)	(0.2152)
_cons	3.6730***	38.2898***	41.6532***	2.1538***
	(0.0823)	(11.2053)	(15.0234)	(0.7827)
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
R^2	0.6073	0.6668	0.5103	0.4311
N	19,153	19,186	19,186	19,186

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

Table 5
Channel 2: financing constraints.

Variables	(1)	(2)	(3)	(4)
	FC	LnRD	Lnpatent	Eff
FinTech	−0.0085**			
	(0.0036)			
$\widehat{FC}$		−4.1426***	−5.9233***	−0.2901***
		(1.2919)	(1.7309)	(0.0903)
_cons	4.9537***	22.5596***	19.1612**	1.0523**
	(0.1959)	(6.3056)	(8.4556)	(0.4400)
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
R^2	0.3979	0.6668	0.5103	0.4311
N	19,181	19,186	19,186	19,186

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

Table 6
Heterogeneity analysis: state-owned firms versus non-state-owned firms.

Variables	State-owned firms			Non-state-owned firms		
	LnRD	Lnpatent	Eff	LnRD	Lnpatent	Eff
FinTech	0.0098	0.0620**	0.0031**	0.0437***	0.0470***	0.0022***
	(0.0223)	(0.0252)	(0.0013)	(0.0104)	(0.0159)	(0.0008)
_cons	1.9533**	−11.2723***	−0.4218***	2.4678***	−9.0221***	−0.3416***
	(0.7952)	(0.8118)	(0.0429)	(0.5490)	(0.6026)	(0.0298)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.7000	0.6114	0.5172	0.6722	0.4585	0.3953
N	5651	5651	5651	13,092	13,092	13,092

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

access to implicit financial subsidies (Chen, Firth, & Xu, 2009; Li, Lin, & Xu, 2020). Therefore, state-owned firms face a lower degree of financing constraints, enabling them to be better funded for R&D (Chan, Dang, & Yan, 2012; Guariglia & Liu, 2014). On the other hand, compared with private firms, state-owned firms normally operate under lower pressure and thus are usually less efficient (Dewenter & Malatesta, 2001), especially in innovation activities with less information disclosure and external supervision. However, with the development of FinTech, the degree of information asymmetry between firms and external investors can be greatly alleviated (Kshetri, 2016; Sedunov, 2017; Sheng, 2021), which forces state-owned firms to invest more effort in their R&D activities, thus improving their innovation output and innovation efficiency. Meanwhile, non-state-owned firms usually face credit discrimination in China's credit market (Lu, Zhu, & Zhang, 2012), thus contributing to their lack of R&D funding (Guariglia & Liu, 2014; Yu et al., 2021). FinTech development greatly eases their financing constraints, thus significantly increasing their R&D expenditure, patent output and innovation efficiency.

4.4.2. *Heterogeneous impact on firms in different geographical locations*

China's economic development has long been unbalanced, with the eastern region developing relatively quickly, the central region developing more slowly, and the western region having the least development. This causes the resources continuously to flow into the eastern region, leading to significant differences in innovation elements among firms in different regions (Acs & Audretsch, 1988; Fritsch, 2002). For this reason, it is necessary that we examine the heterogeneous impacts of FinTech development on firms' innovation by region (Li, 2009).

According to firms' geographical location, we divide the sample into three subsamples for the eastern, central and western regions, and then conduct group regressions. Table 7 reports the results. As we can see, FinTech development significantly contributes to the innovation enhancement of eastern and central firms in all three aspects, but only increases the R&D investment of western firms. In addition, the promotion effect of FinTech development is stronger for firms in the central region than those in the eastern region. Overall, the effect of FinTech development on innovation is stronger for firms in central region.

There are several possible reasons for the above results. First, because the western region is more remote and has the lowest level of financial service coverage, firms usually face severe financing constraints (Hsu et al., 2014). Hence, the development of FinTech can greatly improve the efficiency of financial services in the western region (Li, 2009; Ozili, 2018), thus substantially relieving firms' financing constraints, which in turn promotes a significant increase in firms' R&D input (Brown et al., 2009; Czarnitzki & Hottenrott, 2011). Second, due to the lesser development of the western region, there is a lack of advanced technology and innovative talent in western firms, which causes them to struggle to transform R&D into innovation (Lewin, Massini, & Peeters, 2009; Rao & Drazin, 2002). As a result, the development of FinTech cannot bring significant enhancement in their patent output and innovation efficiency. Third, the eastern region has the advantage of innovation resources and a beneficial business environment, so the optimization effect of FinTech development on its innovation elements is weaker than that of the central region. Thus, the promotive effect of FinTech development on eastern firms' innovation is less than that of the firms in central region.

4.4.3. *Heterogeneous impact on firms with different technological attributes*

Firms' own technological attributes are also an important factor affecting their innovation planning and innovation capability (Nunes, Serrasqueiro, & Leitão, 2012; Shefer & Frenkel, 2005). Thus, we run group regressions to test the heterogeneous impacts of FinTech development on innovation in firms with different technological attributes. Specifically, we divide our sample into high-tech and non-high-tech firms groups based on the "Classification of High-tech Industries (Manufacturing) (2017)" published by the National Bureau of Statistics, and then conduct separate regressions for the two subsamples.

Table 7
Heterogeneity analysis: firms located in different regions.

Variables	Eastern			Central			Western		
	LnRD	Lnpatent	Eff	LnRD	Lnpatent	Eff	LnRD	Lnpatent	Eff
FinTech	0.0227*	0.0342**	0.0017**	0.0730***	0.1202***	0.0061***	0.1031**	0.0624	0.0021
	(0.0126)	(0.0165)	(0.0009)	(0.0250)	(0.0241)	(0.0013)	(0.0397)	(0.0413)	(0.0022)
_cons	2.4781***	−9.8578***	−0.3647***	1.5431	−9.8554***	−0.3695***	−0.7579	−11.6614***	−0.4584***
	(0.5171)	(0.5242)	(0.0268)	(1.4391)	(1.4369)	(0.0733)	(1.1335)	(1.0671)	(0.0606)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.6911	0.5128	0.4352	0.6905	0.5657	0.4948	0.6603	0.5457	0.4650
N	14,167	14,167	14,167	2852	2852	2852	2160	2160	2160

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

The results are shown in Table 8. FinTech development enhances high-tech firms' innovation in all three aspects. However, in non-high-tech firms, FinTech development only boosts patent output and innovation efficiency, while having no significant influence on R&D. That said, FinTech development has greater effects on the patent output and innovation efficiency of non-high-tech firms than it does for high-tech firms. Overall, the effect of FinTech development on innovation is more pronounced for high-tech firms.

The plausible explanation for the results is as follows. High-tech firms' main business is technological innovation. They therefore have few tangible assets and weak collateral capacity, which often leads them to face serious financing constraints in credit markets (Hall, 2002; Yu et al., 2021). However, innovation activities always require enormous capital investment, and the lack of R&D investment is a major impediment to their continuous innovation (Baumann & Kritikos, 2016). Therefore, FinTech development makes a significant contribution to their R&D investment. Meanwhile, the primary reason for non-high-tech firms' low level of innovation is a technology shortage rather than R&D shortage (Nunes et al., 2012; Rammer, Czarnitzki, & Spielkamp, 2009), which explains the insignificant impact of FinTech development on their R&D investment. In addition, since the FinTech development not only reduces the degree of information asymmetry between firms and external investors (Kshetri, 2016) but also enables non-high-tech firms to better understand and learn more about the technologies of advanced firms in the same industry (Del Monte & Papagni, 2003), it contributes more to non-high-tech firms' innovation output and innovation efficiency.

4.5. Endogeneity discussion

In the baseline regression, the FinTech development indicator is based on the number of newly registered FinTech firms at the prefecture level, which is unlikely to constitute a reverse causal relationship with firms' innovation. However, endogeneity may remain in our model because of the omitted variables, despite our inclusion of as many variables as possible that may influence firms' innovation. Thus, we conduct an instrumental variable approach to mitigate potential endogeneity problems.

Considering the prevalence of text mining analysis methods to measure the level of FinTech development in the current literature, we adopt this approach to construct our instrumental variable (IV). Following Li, Wu, and Xiao (2020), we first extract a set of FinTech-related keywords from FinTech-related news and conferences, and then match these keywords with all prefectural cities in China and search for [prefectural cities + keywords] in Baidu news search by year. Finally, we total the number of occurrences of the search and take the logarithm of this number as an IV in our Endogeneity test. The construction of the IV satisfies the requirements both to correlate with the core explanatory variable and exhibit exogeneity, thus making it a reasonable instrumental variable.

Table 9 presents the results of the two-stage regression with IV, in which column (1) shows the first-stage regression results, and columns (2)–(4) provide the second-stage regression results. From the results of the Kleibergen-Paap rk LM test and the Cragg-Donald Wald F test, we find no under-identification and weak instrument problems, proving that the IV is effective. In column (1), the coefficient of IV is significantly positive at the 1% level, suggesting that there is positive relationship between IV and the core independent variable FinTech. In columns (2)–(4), the coefficients of FinTech are all positive and significant, which indicates that our findings still hold after mitigating potential endogeneity.

4.6. Robustness tests

4.6.1. Alternative measure of firms' innovation

For robustness, we first consider alternative measures for the dependent variable. In the baseline model, we select three proxies to measure firm's innovation in terms of R&D input, patent output and innovation efficiency. Likewise, we also select alternative measures of each proxy from these three dimensions in the robustness test. For innovation input, we use the ratio of R&D expenditure to operating income to indicate firms' R&D intensity. For patent output, we consider the number of granted patents as reflective of firms' innovation output, thus taking the logarithm of [1 + the number of granted patents] as a dependent variable in the robustness test. In a similar way, we measure firms' innovation efficiency by adopting the ratio of the logarithm of [1 + the number of granted patents] to the logarithm of R&D expenditure.

According to Eq. (1), we conduct a robustness test with the

Table 9
Endogeneity analysis: instrument variable approach.

Variables	(1)	(2)	(3)	(4)
	FinTech	LnRD	Lnpatent	Eff
IV	1.8410***			
	(0.1334)			
FinTech		0.0387***	0.0483***	0.0022**
		(0.0146)	(0.0165)	(0.0009)
_cons	−2.8281***			
	(0.8834)			
Kleibergen-Paap rk LM statistic P-val	0.0000	0.0000	0.0000	0.0000
Cragg-Donald Wald F statistic	19,914.49	2.0e+04	2.0e+04	2.0e+04
Controls	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
R^2	0.7682	0.5578	0.3538	0.2501
N	19,148	19,148	19,148	19,148

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

Table 8
Heterogeneity analysis: high-tech firms versus non-high-tech firms.

Variables	High-tech firms			Non-high-tech firms		
	LnRD	Lnpatent	Eff	LnRD	Lnpatent	Eff
FinTech	0.0499***	0.0433**	0.0019**	0.0190	0.0612***	0.0032***
	(0.0108)	(0.0173)	(0.0009)	(0.0154)	(0.0175)	(0.0009)
_cons	−0.0126	−9.9371***	−0.3127***	3.6009***	−9.9668***	−0.4170***
	(0.4939)	(0.5338)	(0.0282)	(0.5215)	(0.7987)	(0.0397)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.8007	0.5662	0.4720	0.5923	0.4353	0.3673
N	8655	8655	8655	10,531	10,531	10,531

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

alternative measures of firms' innovation we mentioned above. The results are presented in Table 10. In columns (1)–(3), the coefficients of FinTech are all positive and significant at the 1% level, which means that FinTech development has a positive impact on firms' R&D intensity, the number of granted patents and innovation efficiency. The results are consistent with the baseline results, proving the robustness of our model.

4.6.2. Alternative measure of FinTech development

To avoid possible bias in evaluating the level of FinTech development, we use an alternative measure of FinTech development for the robustness test. In the baseline regression, we take the logarithm of [1 + the number of newly registered FinTech companies] as a proxy of FinTech development at the prefecture level. Since we believe that the cumulative number of FinTech firms can also be a reasonable indicator for the level of FinTech development, we take the logarithm of [1 + the number of cumulative registered FinTech companies] as an alternative measure for independent variable.

Table 11 provides the regression results of the robustness test with alternative measure of FinTech development. In columns (1)–(3), the coefficients of FinTech_cum are all positive and significant at the 1% level, and the coefficient values are close to corresponding coefficient values in the baseline regression. This demonstrates that our results are robust with alternative measure of independent variable.

4.6.3. FinTech lag time

Considering that there may be a time lag in the impact of FinTech development on firms' innovation, we use the time lag of FinTech indicator (L.FinTech) as the core independent variable in our regression for robustness. The results are shown in Table 12. The coefficients of L.FinTech are all positive and significant at the 1% level, which remains consistent with our findings in the baseline regression, indicating that our main findings are robust. The results also strengthen our assertion in endogeneity discussion that there is unlikely to be reverse causality in our model.

4.6.4. Addressing the influence of outliers

There are four municipalities that are directly under China' s central government included in our samples. This could cause bias in our results, because in China municipalities have economic and financial resource advantages over other prefectural cities, and thus always have a higher level of FinTech development. Moreover, firms in municipalities are also more innovative due to their stronger policy support and subsidies. For this reason, we remove the municipality samples in our robustness test to address the influence of outliers. The results are shown in Table 13. In columns (1)–(3), the coefficients of FinTech are all positive and significant at the 1% level, demonstrating that our findings in the baseline regression are valid and robust.

Table 10
Robustness analysis: Alternative measures of firms' innovation.

Variables	(1)	(2)	(3)
	RDintensity	Lngranted	Eff-granted
FinTech	0.0023***	0.0452***	0.0022***
	(0.0004)	(0.0136)	(0.0007)
_cons	0.0270	−9.4151***	−0.3507***
	(0.0225)	(0.5262)	(0.0270)
Controls	Yes	Yes	Yes
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
Province	Yes	Yes	Yes
R^2	0.4496	0.5222	0.4465
N	19,186	19,186	19,186

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

Table 11
Robustness analysis: Alternative measure of FinTech development.

Variables	(1)	(2)	(3)
	LnRD	Lnpatent	Eff
FinTech_cum	0.0388***	0.0499***	0.0024***
	(0.0122)	(0.0168)	(0.0009)
_cons	2.0276***	−10.1671***	−0.3838***
	(0.4399)	(0.4358)	(0.0220)
Controls	Yes	Yes	Yes
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
Province	Yes	Yes	Yes
R^2	0.6669	0.5102	0.4309
N	19,186	19,186	19,186

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

Table 12
Robustness analysis: Lag term of FinTech.

Variables	(1)	(2)	(3)
	LnRD	Lnpatent	Eff
L.FinTech	0.0332***	0.0413***	0.0020***
	(0.0113)	(0.0140)	(0.0007)
_cons	2.0734***	−9.9401***	−0.3673***
	(0.4114)	(0.4417)	(0.0220)
Controls	Yes	Yes	Yes
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
Province	Yes	Yes	Yes
R^2	0.6765	0.5126	0.4346
N	18,128	18,128	18,128

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

Table 13
Robustness analysis: addressing the influence of outliers.

Variables	(1)	(2)	(3)
	LnRD	Lnpatent	Eff
FinTech	0.0392***	0.0475***	0.0023***
	(0.0112)	(0.0148)	(0.0008)
_cons	1.8953***	−9.5255***	−0.3564***
	(0.4155)	(0.4507)	(0.0241)
Controls	Yes	Yes	Yes
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
Province	Yes	Yes	Yes
R^2	0.6556	0.4980	0.4194
N	15,253	15,253	15,253

Standard errors are in parentheses. ***, ** and * indicate significant at the 1%, 5% and 10% levels, respectively.

5. Conclusions

The rapid progress of emerging technologies has driven the continuous integration of the financial industry and technology, resulting in the emergence of FinTech. The development of FinTech can effectively improve the efficiency of financial services supporting the real economy, and thus plays an important role in promoting high-quality development. Therefore, in the context of innovation-driven development, it is of theoretical value and practical significance to examine the impact of FinTech development on firms' innovation.

In this paper, we applied province-industry-year FE regression to a sample of 3620 Chinese listed firms from 2011 to 2021. By taking R&D input, patent output, and innovation efficiency as our measures of firms' innovation, we provide robust evidence that FinTech development significantly facilitates firms' innovation capacity. We also show that the

positive effect is driven by the alleviation of firms' information asymmetry and financing constraints. Specifically, we find that the positive effect of FinTech development on innovation is more pronounced for non-state-owned firms, firms in central region, and high-tech firms.

Overall, our findings demonstrate the crucial role of FinTech development in continuous innovation progress, thus generating important policy implications. First, the government should increase its support for FinTech development. Specifically, the government should set up an assessment system to evaluate the degree of FinTech integration in financial institutions, and formulate corresponding rewards and penalties based on the evaluation results, thus improving the initiatives for financial institutions regarding FinTech application. Second, the government should actively promote the establishment of FinTech infrastructure, such as 5G base stations, big data centers, the Internet of Things, artificial intelligence, blockchain, etc., thus providing a solid foundation for the deep integration of traditional finance and emerging technologies. Finally, regulators should strengthen macro-prudential management to prevent the financial risks that may be brought about by FinTech. FinTech has broadened the geographical and spatial scope of financial services, so it is necessary to explore new regulatory patterns and form a model of technology regulation, enhancing the relevance, immediacy, and effectiveness of regulation in the field of FinTech.

Data availability

Data will be made available on request.

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