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Digital economy and corporate innovation: evidence from Chinese a-share listed firms

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Abstract. This study systematically summarizes the digital economy's impact on corporate innovation based on four influencing mechanisms, namely enterprise digitalization levels, research and development (R&D) efficiency, R&D cooperation, and human capital. It empirically analyzes this impact from the perspectives of effects, mechanisms, and heterogeneity by matching the Chinese provincial-level digital economy evaluation index with the A-share listed companies' patent data. The results show that if the digital economy-level increases by 1% in a province, enterprises' number of invention patent applications will increase by about 3.70 on average. Additionally, its development has significantly improved the digitalization level of enterprises and promoted their R&D efficiency, which in turn fosters enterprise innovation. Finally, the digital economy's impact on enterprise innovation exhibits heterogeneity, showing a more significant innovation effect on low marketization, high industry technology intensity, and private enterprises. Overall, the findings have important theoretical and policy implications for understanding how the digital economy is deeply integrated into the real economy, thereby promoting enterprise innovation.

Keywords: digital economy, corporate innovation, patent

1. Introduction

Since the 21st century, with the new scientific and technological revolution that popularized and expanded digital technology applications, the digital economy has become an important economic development direction worldwide. For instance, the United States launched its "information superhighway" strategy in the 1990s, prioritizing digital economy developments to maintain international competitiveness. The United Kingdom's Digital Britain initiative, launched in 2009, included digital transformation as the country's top-level design priority for the first time. Similarly, Japan has been making efforts to build a "super-smart society" since 2013, releasing the i-Japan and Smart Japan Information Communication Technology (ICT) Strategy. China also introduced the "Internet +" strategy in 2015 to promote its in-depth integration with various economic and social sectors. Overall, it is the consensus that technological progress promotes national innovation. However, unlike the characteristics of previous economic developments, the digital economy presents a new feature, with digital technology acting as the core driving force. This naturally raises the question of how digital economy developments can affect a country's innovation levels.

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China's digital economy is becoming a new driving force for innovation. For example, Zhejiang Province, located in the southeastern coastal area of China, has always been at the forefront of China's digital economy development. Its provincial capital, Hangzhou, has even put forward the goal of becoming "the first digital economy city in China". To this end, Hangzhou has introduced policies related to digital industry and encourage enterprises to carry out digital transformation. Moreover, with the location advantage of Alibaba headquarters, Hangzhou attracts a large number of talents related to digital technology every year, this external network effect also greatly drives the innovation of local enterprises. As a result, the number of valid invention patents in Hangzhou reached 58,559 in 2019, ranking first among the provincial capitals in China[1].

Compared with Zhejiang Province, the economic development level of Guizhou Province in southwest China is relatively backward, and the GDP ranking of the province remains around 22 for many years. Nevertheless, Guizhou Province has always insisted on developing the digital economy, and actively built a data center cluster in Guiyang, the provincial capital, which has successfully attracted a lot of international big data companies such as Apple, Microsoft, Alibaba and Huawei. Driven by these digital economy enterprises, the number of valid invention patents in Guizhou Province exceeded 10,000 for the first time in 2018, of which 1,046 were valid invention patents in the field of big data, accounting for 10.36% of the total. These two examples fully demonstrate that although there are differences in the level of economic development between regions, but it is still possible to promote corporate innovation through the development of the digital economy.

Therefore, this study focuses on China, the largest developing country in the world, to study how digital economy developments and their internal influencing mechanisms affect enterprise innovation. Sorting these issues will provide a micro-explanation of how these developments affect the real economy.

Existing studies mostly analyze the factors affecting enterprise innovation from the perspectives of internal governance levels, high-level characteristics and external financial markets, institutional environments, and the protection of property rights [1, 2]. However, few studies have focused on how digital economy developments impact enterprise innovation. Thus, constructing a digital economy evaluation index may be the key to investigating this problem, as an enterprise is not only a carrier of digital economy empowerment but also a micro subject of innovation. The existing literature mainly selects indexes based on Internet development levels or ICT investments to synthesize the digital economy's evaluation indexes. For example, the European Union (EU) has always attached importance to the development and statistics of its digital economy. In 2014, it released the Digital Economy and Society Index, a synthetic index describing the digital economy's degree of development in EU countries. It is calculated according to 31 secondary indicators, encompassed within five major topics: broadband access, human capital, Internet application, digital technology application, and digital public service degree. Furthermore, the Organization for Economic Cooperation and Development compared and evaluated digital economy developments in countries around the world with 38 indicators related to ICT investments in infrastructure and ICT applications. Most of these indicators measure these developments at the national level, based on digital economy infrastructures (e.g., broadband access and ICT infrastructure investments) and applications (e.g., digital technology and ICT application). Drawing on the above ideas as well as the China National Bureau of Statistics' definition of digital economy and industry classification standards, presented in May 2021, this paper constructs digital economy evaluation indicators at the provincial level from the perspectives of "digital industrialization" and "industrial digitalization" to more accurately identify the digital economy's impact on regional enterprises' economic activities.

The contributions of this study are as follows. First, it enriches the research on the influencing factors of enterprise innovation. As the results show, the digital economy's development is an important factor influencing the innovation of local enterprises. Thus, this study provides empirical evidence for the realization of an innovation-driven development strategy through the construction of a "digital China".

Second, this paper systematically examines the mechanisms that influence the digital economy's impact on enterprise innovation and enriches the relevant literature assessing this relationship. After empirically testing the four main influencing mechanisms, namely enterprise digitization level, research and development (R&D) efficiency, the results further confirm that the digital economy significantly promotes enterprise innovation.

Third, based on the two perspectives of digital industrialization and industry digitalization, we construct a digital economy evaluation index, using the principal component analysis method, and test its validity. Compared to previous research, this study's assessments are more comprehensive, accurate, and effective, and can serve as a reference for subsequent empirical studies on the digital economy.

The remainder of this research is organized as follows. Section 2 posits the influencing mechanisms of the digital economy and the research hypotheses. Section 3 introduces the measurement model, variable measures, and data sources. Section 4 presents the main results, as well as the underlying mechanisms and characteristics of heterogeneity. Finally, the conclusions are offered in Section 5.

2. Theoretical analysis and research hypotheses

In the digital economy era, data have become an important catalyst for enterprises, innovation activities and as a new production factor, it is believed to have the capacity to create new knowledge and influence enterprises' decisions [3]. However, because of data's virtual nature, it must be combined with digital technology to play a role in enterprises' innovation processes. On the one hand, digital economy developments drive the popularization and expansion of digital technology application fields, directly promoting enterprises' digitization levels and speeding up their innovation processes as a result. On the other hand, owing to the non-competitive characteristics of data [4], enterprises can exchange and share data with stakeholders (e.g., financial institutions and other investors) and other innovation partners (e.g., universities, scientific research institutions, and other enterprises) through digital technology. This is conducive to reducing information asymmetry and improving enterprise innovation by easing financing constraints. Thus, this study discusses the digital economy's impact on enterprise innovation from four perspectives: enterprise digitization level and R&D efficiency.

2.1. Improvements in enterprise digitization levels

The digital economy's promotion effect on enterprise digitization levels is mainly reflected in three aspects. First, digital economy developments drive digital infrastructure construction improvements in the regions where the enterprises are located and provide a good "digital environment" for enterprises' digital transformation. Second, they promote data becoming a key production factor and change enterprises' production, sales, and organizational modes (e.g., to obtain digital dividends brought about by data elements, enterprises are more motivated to improve their digitization levels). Third, they also encourage the spread and diffusion of digital technology. As the number of digital transformation enterprises in the same region increases, the remaining enterprises will take the initiative to introduce digital technology and improve their level of digitalization.

A large body of literature has discussed the relationship between enterprise digitization levels and innovation. The consensus is that digital technology has changed the innovation processes of enterprises. The traditional enterprise innovation process is usually linear and requires a long time to proceed from idea generation to R&D, product manufacturing, and sales. However, driven by digital technology, enterprises' innovation processes are faster, the related costs are lower, and innovation efficiency is higher. Specifically, in the R&D investment phase, digital simulations and twinning technologies significantly reduce the R&D costs of enterprises [5]. In the product manufacturing phase, the Internet of Things technology enables customers to participate in product design, development, and sales through virtual customer environments [6]. In the product sales phase, enterprises can build online platforms that rely on digital technology to improve transaction efficiency and realize the commercialization of innovation achievements.

Williamson and Yin [7] find that Chinese enterprises encapsulate the potential innovation points through their digital processing of user data, and use of digital technologies to accelerate the innovation process and effectively promote enterprise innovation. Several empirical studies also demonstrate that the diffusion of digital technology through the Internet has greatly reduced Chinese enterprises' information acquisition costs, and significantly improved innovation resource allocation and performance. For example, using Chinese listed companies' data from 2009 to 2015, Wang et al. [8] find that an increase of 1% in per capita Internet access in cities where the enterprises are located will effectively increase the number of authorized invention patents by 8.07%. Similarly, Shen and Yuan [9] use China Industrial Enterprise Database data from 2011 to 2013 and determine that the Internet can significantly increase the number of enterprise invention patents. In this context, we propose research hypothesis 1: the digital economy directly promotes improvements in enterprise digitization, accelerates the innovation process, and stimulates enterprise innovation as a result.

2.2. Improvements in R&D efficiency

Sufficient R&D funding is an important necessity for enterprise R&D efficiency. However, because of innovation's strong output uncertainty [10] , long cycle, and low outcome probability, it is often difficult for investors to search and process information related to a company's innovation strategy. It is also difficult for financial institutions to accurately measure the costs and income of innovation activities. In other words, information asymmetry often exists between enterprises and stakeholders [11]. All these problems lead to low efficiency in enterprise R&D and insufficient innovation output.

Digital technologies, such as big data, cloud computing, artificial intelligence, and block chain, are powerful tools for breaking information silos, promoting information openness, and facilitating information sharing. Relying on digital technology and platforms, online information-sharing channels can be established between enterprises and financial institutions to help the latter understand the former's capital needs in a timely manner, alleviate information asymmetry, and promote efficient and accurate connections between capital supply and demand. For instance, the Ministry of Industry and Information Technology of China set up an online national industry-finance cooperation platform in February 2021. By the end of October, more than 101,000 enterprises and 797 financial institutions had joined the platform and signed contracts. The enterprises were granted a credit totaling 95.91 billion yuan. Thus, they obtained a financial guarantee for improving their R&D efficiency. Based on the above assessment, we propose research hypothesis 2: the digital economy induces enterprises to increase innovation by improving their R&D efficiency.

3. Empirical strategies and data

3.1. Empirical model

The empirical model can be represented as follows:

$$PatInv_{it} = \beta_0 + \beta_1 Digital\_econ_{jt-1} + \beta_2 X_{it-1} + \lambda_t + \delta_i + \varepsilon \quad (1)$$

where the dependent variable $PatInv_{it}$ reflects the number of invention patent applications of enterprise i in year t. The core independent variable $Digital\_econ_{jt-1}$ represents the digital economy level of province j where enterprise $i$is located in $t-1$ year. The coefficient β_1 measures the digital economy's impact on enterprise innovation. If it is significantly greater than zero, then the digital economy has a promoting effect on local enterprise innovation. X represents a series of enterprise- and macro-level control variables. To avoid reverse causality's interference with the regression results, this study processed both core independent variables and control variables with a one lagged period. Finally, λ_t and δ_i are the time- and firm-fixed effects, respectively, and ε is the random error term. This model effectively controls for the influence of unobserved factors on firm innovation at the individual level.

3.2. Variable measurements

3.2.1. Digital economy evaluation indicators

In May 2021, the National Bureau of Statistics of China published the Statistical Classification of Digital Economy and its Core Industries (2021) (hereinafter referred to as the Digital Economy Classification). It clearly defines the concept of digital economy and divides its core industries into digital industrialization and industrial digitalization. Digital industrialization refers to the digital economy's core industries, namely digital product manufacturing, the digital product service industry, the digital technology application industry, and the data-driven industry that provides digital infrastructure and technology support for industrial digital development, representing the foundation of the digital economy development. Industrial digitization refers to the application of digital technology in traditional industries to increase output and improve efficiency. The Digital Economy Classification also explains the specific scope of the national economic industry classifications and is consistent with the notes on the 2017 Industry Classification of the National Economy.

According to the definition and scope of the core industries, combined with the available data, we selected the following indicators to measure digital industrialization and industrial digitalization. For digital industrialization, the digital product manufacturing industry mainly refers to computer communications and other electronic equipment manufacturing, such as computers, cable lines, and mobile phone base stations. Thus, we selected "number of computers at the end of the year", "optical cable length", and "number of mobile phone base stations" as indicators to measure the digital product manufacturing industry. Additionally, as e-commerce is an important digital product and service transaction, this study used "e-commerce purchase amount" and "e-commerce sales volume" to measure the digital product service industry's degree of development. We further selected "software business income" and "telecommunication business income" as indicators of the digital technology application industry, as the software and telecommunications industries are representative of digital technology applications. Finally, Internet-related services are key to supporting the role of data-driven industries. Thus, "Internet broadband access port", "IPv4 address number", "domain name number", and "web page number" are used to measure the data-driven industry's degree of development.

In terms of industrial digitalization, the Digital Economy Classification defines industries that embody the deep integration of digital technology and the real economy as those that promote digital efficiency. These include intelligent agriculture, intelligent manufacturing, digital finance, and digital commerce. Therefore, the number of enterprises related to the above digitalization application in a region can reflect the regional industrial digitalization development level to a certain extent. Based on this idea, we initially searched for particular keywords, such as "smart agriculture", "smart manufacturing", "smart production", "smart transportation", "smart logistics", "digital commerce", "digital finance", "digital mining", "smart education", "smart healthcare", "smart life", and "digital services" on the "Tianyancha" website. Then, we obtained samples of companies whose names or business scopes are summarized using the above keywords. To ensure robustness, we excluded companies whose operation times were less than one year or whose operation statuses were abnormal, such as suspension, dissolution, rescission, etc. Finally, we calculated the number of industrial digitalization companies in each province and measured the development level of regional industrial digitalization. In this regard, the more companies there are, the higher the regional industrial digitalization level will be. To standardize each indicator's data, we used a principal component analysis to obtain the digital economy evaluation indicators. These were standardized between 1 and 10 and denoted as Digital_Econ. The measurement methods for these indicators are listed in Table 1.

Table 1. Measure method of digital economy evaluation indicators

First-level Indicator	Second-level Indicator	Third-level Indicator	Original Indicator
Digital economy evaluation indicators	Digital industrialization	Digital product manufacturing industry	Number of computers at the end of the year
			Length of optical cable
			Number of mobile phone base stations
		Digital product service industry	E-commerce purchase amount
			E-commerce sales amount
		Digital technology applications industry	Software business income
			Telecommunication business income
		Data element driven industry	Internet broadband access port
			Number of IPv4 address
			Number of domain name
			Number of webpage
	Industrial digitalization	Industry that promotes digital efficiency	Number of companies with the keywords of intelligent agriculture, intelligent manufacturing, intelligent production, intelligent transportation, intelligent logistics, digital commerce, digital finance, digital mining, intelligent education, intelligent medical treatment, intelligent life and digital services

Furthermore, we illustrate the effectiveness of the digital economy evaluation index used in this study by comparing it to prior research reports and existing literature. Guangdong, Jiangsu, Shandong, Zhejiang, Beijing, and Shanghai take the lead in China's digital economy according to the overall digital industrialization and industrial digitalization scale data of provinces and cities in 2020, as reported in the White Paper on China's Digital Economy [12]. To facilitate a comparison with the above results, this study calculated the mean values of the digital economy evaluation indexes for each province during the sample period (Table 2). Based on this analysis, our measurement results appear to be essentially consistent with the research conclusions of the White Paper on China's Digital Economy (2021). Therefore, the results of this study can be considered valid.

Table 2. Provincial mean ranking of digital economy evaluation indicators

Ranking	Province	Mean of Indicators	Ranking	Province	Mean of Indicators
1	Guangdong Province	9.0824	16	Shanxi Province	5.7461
2	Beijing	8.8635	17	Guizhou Province	5.6636
3	Shanghai	8.5280	18	Guangxi Zhuang Autonomous Region	5.4937
4	Zhejiang Province	8.1261	19	Heilongjiang Province	5.4725
5	Jiangsu Province	8.0768	20	Jiangxi Province	5.4669
6	Fujian Province	8.0057	21	Chongqing	5.3743
7	Sichuan Province	7.2487	22	Shaanxi Province	5.3587
8	Shandong Province	7.0091	23	Jilin Province	5.3514
9	Hebei Province	6.9507	24	Xinjiang Uygur Autonomous Region	5.2389
10	Hubei Province	6.7314	25	Hainan Province	5.0806
11	Anhui Province	6.5640	26	Yunnan Province	5.0646
12	Henan Province	6.5160	27	Gansu Province	4.3960
13	Liaoning Province	6.3489	28	Ningxia Hui Autonomous Region	4.2945
14	Tianjing Province	6.2890	29	Qinghai Province	4.1955
15	Hebei Province	5.7490	30	Inner Monggol Autonomous Region	4.1953

Source: collated by author

3.2.2. Enterprise innovation

The existing literature mainly measures the level of enterprise innovation from two perspectives: R&D investment and patent output. R&D investment assessments mainly use the enterprise R&D expenditure index, while patent applications, patent authorizations, and the number of citations are used to measure patent output. Due to China's introduction of many innovation incentive policies, listed companies may falsely report their R&D expenditures [13]. Therefore, this study used the patent application number (PatApply) to measure the innovation capability of enterprises. According to the types of patents, we also used the number of invention patent applications (PatInv) to estimate the digital economy's impact on high-quality innovation. To determine its impact on low-quality innovation, we selected the number of utility model and appearance design patents (PatUty). In the subsequent robustness test, we adopted patent authorizations and citations to measure enterprises' innovation capabilities.

3.2.3. Control variables

First, this study controlled for the age of enterprises (Age), considering that enterprises have different motivations to choose innovation strategies at different development stages. Second, we controlled the variables related to enterprise profitability, because it is the premise of R&D investment. These include enterprise-scale (Size), rate of return on total assets (Roa), business revenue growth rate (Growth), asset-liability ratio (Lev), the ratio of fixed assets (Fix), and enterprise cash flow (Cflow). Third, considering that the higher the level of corporate governance, the better it can ensure the smooth progress of enterprise innovation activities [14], we also controlled for board independence (Indep) and CEO duality (Duality). Finally, macro-level economic variables were controlled, including GDP per capita (Pgdp) and local financial expenditure on science and technology (Fin) in the province where the firm is located. All variables were winsorized at the 1% and 99% levels to mitigate the impact of outliers. Table 3 presents the variables' specific definitions and descriptive statistical results.

Table 3. Summary statistics

Variables	Definition	Mean	S.D.	Min	Median	Max
Digital_ Econ	Principal component analysis	7.68	1.33	3.09	7.91	9.83
PatApply	Ln (total patents + 1)	1.81	1.73	0.00	1.79	9.57
PatInv	Ln (patents for inventions + 1)	1.29	1.45	0.00	1.10	9.03
PatUty	Ln (patents for utility + patents for design + 1)	1.33	1.55	0.00	0.69	8.70
Age	Ln (age of enterprise from establishment)	2.86	0.32	1.39	2.89	3.95
Size	Ln (total assets)	22.16	1.32	15.98	22.00	28.52
Roa	Net profit / total assets	0.42	0.22	0.01	0.41	8.61
Growth	The growth rate of business revenue	0.04	0.13	-6.78	0.04	8.44
Lev	Total liabilities /total assets	0.07	0.47	-20.59	0.08	14.87
Fix	Total fixed assets / total assets	0.49	16.36	-1.31	0.11	1,878.37
Cflow	Net cash flow / total assets	0.21	0.16	0.00	0.18	0.91
Indep	Number of independent directors / total number of directors	0.38	0.06	0.18	0.36	0.80
Duality	= 1 if a firm's CEO have the dual role of Board Chairman; = 0 otherwise	0.15	0.21	0.00	0.01	0.89
Pgdp	Ln (GDP per capital)	1.81	1.73	0.00	1.79	9.57
Fin	Ln (local government expenditure on science and technology)	1.29	1.45	0.00	1.10	9.03

3.3. Data

The relevant data on digital industrialization stem from the China Statistical Yearbook and the China Internet Development Statistical Report, whereas the data on industrial digitalization come from the enterprise operation information disclosed by the Tianyancha website. It should be noted that because the China Statistical Yearbook began to collect e-commerce purchase amount and transaction volume data in 2014, the sample period for the digital economy evaluation indicators constructed in this study was from 2013 to 2019, due to limited data availability. Additionally, we obtained companies' patent data from the State Intellectual Property Office and all enterprise financial data from the CSMAR database. Using the existing literature's processing methods as a reference, we excluded all ST and ST* enterprises, financial industry enterprises, samples with missing key variables, and samples with asset-liability ratios greater than 1. As a result, we obtained 14,894 enterprises with annual observations.

4. Empirical results and discussion

4.1. Baseline results

This study uses a panel fixed-effects model to test the digital economy's overall impact on enterprise innovation. Table 4 reports the regression results of Model (1). Considering that the fixed effect will affect the regression coefficient's size, this study strictly controls the enterprises' fixed effects and year-fixed effects in each column to ensure robustness. The Digtal_Econ coefficients in columns (1) to (3) are significantly positive at the 1% level, indicating that the higher the digital economy's development, the more it can promote local enterprises' innovation levels. Considering that invention patents have the highest innovation quality, the regression results in Column (2) serve as an example to illustrate the study's economic significance. In the sample period, the average number of enterprise invention patent applications (without taking the logarithm) is 21.85. Therefore, every 1% increase in digital economy development within the province where an enterprise is located is conducive to an average increase of 3.70 invention patent applications. Overall, the above results indicate that digital economy developments have significantly improved enterprises' overall innovation levels.

Table 4. Digital economy and enterprise innovation

	(1)	(2)	(3)
	PatApply	PatInv	PatUty
Digtal_Econ	0.2082***	0.1692***	0.1614***
	(0.0573)	(0.0481)	(0.0499)
Age	-0.1296	-0.0255	0.1368
	(0.2645)	(0.2265)	(0.2467)
Size	0.0084	0.0277	-0.0036
	(0.0324)	(0.0267)	(0.0276)
Lev	-0.0069	0.0125	0.0380
	(0.1093)	(0.0846)	(0.0972)
Roa	1.1310***	0.7581***	1.0712***
	(0.1956)	(0.1598)	(0.1712)
Cash	-0.0025	0.0021	-0.0091
	(0.0461)	(0.0371)	(0.0418)
Growth	0.0278*	0.0249*	0.0182
	(0.0159)	(0.0131)	(0.0142)
Fixed	0.4084***	0.2690**	0.2804**
	(0.1477)	(0.1216)	(0.1293)
Indenp	-0.0610	-0.0662	-0.0052
	(0.3026)	(0.2160)	(0.2794)
Shaercen	0.4077**	0.2017	0.3404**
	(0.1655)	(0.1272)	(0.1519)
Pgdp	-0.1665	-0.1538	-0.1496
	(0.1212)	(0.1008)	(0.1103)
Fin	0.0307	0.0129	0.0345
	(0.0511)	(0.0416)	(0.0478)
Constant	2.0194	1.0518	1.2188
	(1.5776)	(1.3410)	(1.3818)
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Observations	14,894	14,894	14,894
Within R^2	0.0142	0.0152	0.0104

Note: Significance levels at 10%, 5%, and 1% levels are denoted by *, **, and ***, respectively. In parentheses are heteroscedasticity robust standard errors of the estimated coefficients.

4.2. Endogenous problems

Although our digital economy evaluation indicator is a macro-variable at the regional level and is less likely to be affected by individual enterprises' innovation behaviors, the estimation results may still be biased and inconsistent, because of omitted variables and measurement bias. Thus, this study adopts the instrumental variables method to alleviate the endogeneity problem. Specifically, the 2007 ICT capital input by sector in each province (from the 2007 input-output table) serves as an instrumental variable for an enterprise's digital technology application level. The effectiveness of this instrumental variable is reflected in the following two aspects. First, the higher the ICT capital investment of the province where the enterprise is located, the higher the level of digital industrialization and industrial digitalization in the province. This further affects the popularization and development of digital technology and makes it easier for enterprises to access and apply digital technologies to meet relevant conditions. Second, this indicator is a historical instrumental variable. With the continuous changes and developments in digital technology, the 2007 ICT capital input struggles to affect current enterprise innovation decisions to meet the externality condition. Even if there is an impact, it is only through the indirect channel of promoting the use of digital technologies. Thus, this study uses the 2007 ICT capital input by sector interaction term in each province and the national Internet penetration rate in the previous year, stemming from the Statistical Report on the Development of Internet in China, as the instrumental variable for enterprises' digital technology application levels.

Table 5 reports the test results. In the first-stage regression results, shown in column (1), the relationship between enterprises' digital technology application levels and the interaction item (IV) (between the 2007 ICT capital input by sector in each province and the national Internet penetration rate of the previous year) is significantly positive at the 1% level. This indicates that, historically, the more industries invest in ICT capitals in the province where the enterprises are located, the more likely local enterprises are to apply digital technologies. The two-stage regression results from columns (2) to (4) show that digital technology's influence on enterprise patent quality is still significantly positive at the 1% level. The instrumental variable passes the insufficient identification and weakness tests, indicating its appropriateness.

Table 5. Estimated results of instrumental variables

	(1)	(2)	(3)	(4)
	Digtal_Econ	PatApply	PatInv	PatGen
IV	0.0236***			
	(0.0062)			
Digtal_Econ		0.8410**	0.6409**	0.9980***
		(0.3882)	(0.3193)	(0.3662)
Controls	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Observations	14,894	14,894	14,894	14,894
Kleibergen-Paap rk LM	—	1,146.729	1,146.729	1,146.729
Kleibergen-Paap rk Wald F	—	1,359.239	1,359.239	1,359.239

Note: In the parenthesis is the robust standard error, in the brackets is the p-value of the corresponding test statistic, and in the brace is the critical value of the Stock-Yogo test at the 10% level.

4.3. Robustness test

4.3.1. Replacing the explanatory variables

This study further divides the digital economy's development indicators into two levels, digital industrialization (Digtal_Ind) and industry digitization (Ind_Digtal), and carries out a regression. By comparing the regression results of the first and last three columns in Table 6, it appears that industrial digitalization has a more significant promotion effect on enterprise innovation than digital industrialization, perhaps because the latter refers to the provision of digital technology, products, services, and infrastructures for industrial digital development. This emphasizes the need to improve the production efficiency of traditional industries through data elements and digital technology, which can better reflect the integration of digital technology and the real economy. Only when enterprises deeply integrate digital technology into their business practices, including their production, operation, and management processes, can the digital economy fully play its role in promoting enterprise innovation.

Table 6. Estimate results of replacing explanatory variables

	Digital Industrialization			Industrial Digitization		
	(1)	(2)	(3)	(4)	(5)	(6)
	PatApply	PatInv	PatGen	PatApply	PatInv	PatGen
Digtal_Ind	0.0723**	0.0554**	0.0621**			
	(0.0291)	(0.0236)	(0.0258)			
Ind_Digtal				0.1274***	0.1029***	0.0910**
				(0.0473)	(0.0373)	(0.0385)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,894	14,894	14,894	14,894	14,894	14,894
Within R^2	0.0095	0.0118	0.0062	0.0096	0.0120	0.0061

Note: In above regression results, both the year fixed effects and the firm fixed effects are controlled. The following tables are the same.

4.3.2. Replacing the explained variables

In this study, we used the final number of granted patent applications (PatGrant) and the number of patent citations (PatCite) as substitutes for the explained variables. Table 7 reports the regression results. The digital economy evaluation indicator's estimated coefficient is always significantly positive, whether the explained variable is the number of granted patents or the number of citations. Thus, the digital economy can improve both the quantity and quality of enterprise innovation.

Table 7. Estimate results of replacing explained variables

	Number of Granted Patents			Number of Patent Citations		
	(1)	(2)	(3)	(4)	(5)	(6)
	PatGrant	PatGrantInv	PatGrantUty	PatCite	PatCiteInv	PatCiteUty
Digtal_econ	0.1677***	0.1486***	0.1614***	0.1368***	0.1028***	0.0846***
	(0.0517)	(0.0461)	(0.0499)	(0.0305)	(0.0249)	(0.0238)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,894	14,894	14,894	14,894	14,894	14,894
Within R^2	0.0163	0.0094	0.0104	0.0241	0.0216	0.0130

4.3.3. Deleting special samples

Due to the unique access to political and economic resources, the number of listed companies in municipalities directly under the central government tends to be relatively large and their innovation outputs tend to be relatively high, which may affect the estimation results. During the sample period, about one-third of the enterprises did not apply for patents. These types of enterprises are more likely to be located in regions with low levels of digital economy development, which may also affect the estimated results. To eliminate the interference of special samples, we removed the enterprises located in these particular regions and re-estimated Model (1). As Table 8 shows, the digital economy evaluation index coefficient is still significantly positive after the special samples were deleted, indicating the robustness of this study's conclusions.

Table 8. Estimate results of deleting special samples

	Delete the Sample of Enterprises in Provinces with Advanced Digital Economy			Delete Business Samples That Have Never Applied for A Patent		
	(1)	(2)	(3)	(4)	(5)	(6)
	PatApply	PatInv	PatGen	PatApply	PatInv	PatGen
Digtal_econ	0.2194***	0.1632***	0.1672**	0.2481***	0.2158***	0.2006***
	(0.0714)	(0.0601)	(0.0683)	(0.0679)	(0.0679)	(0.0732)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6,625	6,625	6,625	9,591	9,591	9,591
Within R^2	0.0211	0.0225	0.0158	0.0295	0.0321	0.0168

4.4. Mechanism analysis

We used text mining to search for keywords and count the word frequency in enterprises' annual reports. We initially selected the Internet, big data, cloud computing, blockchain, artificial intelligence, Internet of Things, 5G, digitalization, informatization, and intelligence, 10 words that are most related to digitalization. Subsequently, we counted the frequency of these 10 words in the annual reports, using the jieba lexicon. This total word frequency is the measure indicator of an enterprise's degree of digitization (Digtech). The larger the indicator, the higher the digitization level, representing an enterprise that has introduced and used digital technologies related to digital transformation. As this index has an obvious "right skew" feature, we added 1 to it and took a logarithmic treatment approach in the regression. The regression results in column (1) of Table 9 show that the Digtal_econ coefficient is significantly positive at the 1% level, indicating that the digital economy is indeed conducive to improving the digitization level of enterprises. From an economic perspective, every 1% increase in the digital economy development indicator improves the digital level of local enterprises by 21.6%.

Table 9. Mechanism test: improve enterprise digitization level and R&D efficiency

	Digitization Level	R&D Efficiency	
	(1)	(2)	(3)
	Digtech	RDSpendratio	RDPersonratio
Digtal_econ	0.2156***	0.0097***	0.0397***
	(0.0569)	(0.0032)	(0.0142)
Controls	Yes	Yes	Yes
Observations	14,894	12,774	10,841
Within R^2	0.2483	0.0097	0.0084

This study further adopts the ratio of invention patent applications to R&D expenditure (RDSpendRatio) and the ratio of invention patent applications to R&D personnel (RDPersonRatio) to measure the R&D efficiency of enterprises. The regression results are shown in Columns (2) and (3) of Table 9. The Digtal_econ coefficients are both significantly positive at the 1% level, suggesting that the digital economy also contributes to improving enterprises' R&D efficiency.

4.5. Heterogeneity analysis

4.5.1. Regional institutional environment, industry technology intensity, and the nature of enterprises

Regarding regional institutional environments, where the digital economy plays an innovative role, local protection forces are stronger in areas with lower degrees of marketization, leading to market mechanisms failing to play a decisive role in the allocation of innovative resources. In this case, enterprises have reduced incentives to innovate. Even if they obtain subsidies for R&D funds, they may not be able to allocate them to innovation projects that have market value. However, the digital economy can enhance the competition level of local industries and improve the efficient flow of innovation resources between regions through online platforms and digitization. Therefore, the digital economy may play a stronger role in promoting enterprise innovation in regions with low marketization.

To determine the degree of regional marketization, we used Wang et al.'s [15] study on various Chinese provinces' marketization processes as a reference. The samples were grouped according to the median to test whether there are significant differences in the innovation effect of digital economy developments in regions with different degrees of marketization. The first two columns of Table 10 show the subsample regression results divided by the degree of marketization. The explained variable is the number of enterprise invention patents. Overall, the promotion effect of digital economy developments on enterprise innovation output is more significant in regions with lower marketization degrees, perhaps because the digital economy can promote the diffusion and sharing of knowledge, information, and technology between different regions. This is conducive to breaking down barriers in the free flow of data and improving enterprises' efficient allocation of innovative resources. Nonetheless, this result implies that more attention should be paid to promoting enterprise innovation through digital economy developments in regions with low marketization.

Table 10. Heterogeneity test

	High Marketization Degree	Low Marketization Degree	High Technology Intensity	Low Technology Intensity	State-owned Enterprises	Private Enterprises
	(1)	(2)	(3)	(4)	(5)	(6)
	PatInv	PatInv	PatInv	PatInv	PatInv	PatInv
Digtal_econ	0.1570*	0.2219***	0.2571***	0.0895	0.1016	0.2330***
	(0.0918)	(0.0699)	(0.0836)	(0.0708)	(0.0715)	(0.0627)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	7,445	7,449	7,456	7,438	5,209	9,615
Within R^2	0.0145	0.0258	0.0229	0.0136	0.0320	0.0120

Considering the varying demands for digital technology in different industries, the digital economy's impact on enterprise innovation in different technology-intensive industries also varies. For high-technology-intensive industries, the use of digital technology is necessary to improve R&D efficiency, but for enterprises in low-technology-intensive industries, innovation uncertainty and information asymmetry are relatively small. Therefore, the digital economy may have a more significant effect on enterprise innovation in industries with a higher technology intensity. Based on Hsu et al. [16], this study adopts the median growth rate of R&D expenditure in the same year as a proxy variable of industry technology intensity to explore the digital economy's impact on the innovation output of technology-intensive enterprises in different industries. Columns (3) and (4) of Table 10 report the heterogeneity analysis based on industry technology intensity. The explained variable is the number of enterprise invention patents. The results show that digital economy developments have a more significant effect on enterprise innovation in technology-intensive industries. A possible explanation is that high-technology-intensive industries need to enhance enterprise competitiveness through innovation. As such, they pay more attention to R&D investments, which enhance the digital economy's innovation role. This result also means that enterprises in low-tech industries should acknowledge the innovation role of the digital economy, and strengthen the deep integration of digital technology and enterprise innovation activities to enhance their competitiveness.

Compared with private enterprises, state-owned enterprises have more political advantages in terms of resource acquisition. Thus, they may be less motivated to innovate. To examine this relationship, the samples were divided into state-owned and private enterprises according to their nature. The subsample regression results are shown in Columns (5) and (6) of Table 10. The explained variable is the number of enterprise invention patents. As shown, digital economy developments significantly improve the innovation level of private enterprises, but not state-owned enterprises.

5. Conclusions and policy recommendations

In the digital economy era, digital technology is becoming a new engine for promoting enterprise innovation. This study discusses the digital economy's influence on enterprise innovation from four perspectives: enterprise digitization levels and R&D efficiency. According to the National Bureau of Statistics' definition of digital economy and industry classification standards, we use principal component analysis, construct novel digital economy development indicators at the provincial level in China, and employ the data of A-share listed companies in Shanghai and Shenzhen from 2013 to 2019 to empirically examine the digital economy's impacts and its mechanisms. The main research conclusions are as follows. First, digital economy developments have significantly improved the innovation level of enterprises. On average, a 1% increase in the digital economy in provinces where companies are located increases the number of invention patents filed by local companies by approximately 3.70. Second, the digital economy has significantly improved enterprises' digitization levels, R&D efficiency, R&D collaboration, and the accumulation of highly skilled human capital, thus promoting enterprise innovation. Third, there is significant heterogeneity in the digital economy's impact on enterprise innovation. For enterprises with a low degree of marketization, high industry technology intensity, and private enterprise nature, the digital economy's innovation promotion effect is more significant.

Based on the results, this study proposes three policy implications for improving enterprises' innovation levels in a digital economy. First, to achieve the strategic goal of "entering the forefront of innovative countries", governments should attach importance to developing the digital economy, accelerating the promotion of digital industrialization, and actively promoting industrial digitalization. Second, governments should also actively promote the deep integration of digital technology with the real economy and encourage enterprises to transform themselves digitally. The results of this study show that digital economy developments can improve enterprises' digitization levels and as a result, their innovative capabilities. On the one hand, to optimize the enterprise innovation process and improve innovation efficiency, enterprises need to actively introduce and apply various digital technologies to form an innovation system with data as the innovation element and digital technology as the innovation driving force. On the other hand, governments should also guide enterprises in their process of adapting to digital economy development trends and provide a good environment for their digital transformation. Third, as the mechanism test shows, developments in the digital economy promote the expansion and utilization of data resources, as well as R&D cooperation between enterprises and other innovation entities, thus improving the innovation level of enterprises. Governments can explore the development and trading system of data resources by establishing a public data resource trading platform and data trading service guarantee mechanism. They should also encourage data sharing and trading among enterprises, universities, research institutions, and other innovative partners.

Finally, as with all research, this study has some limitations that can be expanded in the future. First, in terms of data, this study constructed development indicators for China's digital economy at the provincial level from 2013 to 2019. Future research can further expand this time frame based on data availability. Second, regarding innovation output, we measured enterprises' innovation levels based on patent applications, authorizations, and citation data. However, these indicators can only represent innovation quality to a certain extent. Thus, future studies could introduce more indicator data related to enterprise innovation quality. Third, in the context of digital economy developments, subsequent research can further explore how improvements in enterprises' digitization affect the quality of their innovations to expand the relevant research in the fields of digital economy and enterprise innovation.

Note

[1]Data source: http://zj.people.com.cn/n2/2020/0401/c186949-33918822.html.

References

[1] Manso G., (2017). Creating Incentives for Innovation. *California Management Review. 60*, 18~32.

[2] He J., Tian X., (2018). Finance and Corporate Innovation: A Survey. *Asia-Pacific Journal of Financial Studies. 47*, 165~212.

[3] Jones C. I., Tonetti C., (2020). Nonrivalry and the Economics of Data. *American Economic Review. 110*, 2819-58.

[4] Acquisti A., Taylor C., Wagman L., (2016). The economics of privacy. *Journal of economic Literature, 54*, 442-92.

[5] Nambisan, S., Wright, M., Feldman, M., (2019). The Digital Transformation of Innovation and Entrepreneurship: Progress, Challenges and Key Themes. *Research Policy. 48*, 103773.

[6] Lyytinen, K., Yoo, Y., Boland Jr, R.J., (2016). Digital Product Innovation within Four Classes of Innovation Networks. *Information Systems Journal. 26*, 47-75.

[7] Williamson P. J., Yin E., (2014). Accelerated Innovation: The New Challenge from China. *MIT Sloan Management Review. 55*, 27.

[8] Wang J J, Guo S L, Zhang L P., (2018). The Impact of the Internet on the Performance and Mechanism of the Enterprise Innovation:An Explanation Based on Open Innovation. *Nankai Economic Studies. 34*, 170-190.

[9] Shen G. B, Yuan Z. Y., (2020). The Effect of Enterprise Internetization on the Innovation and Export of Chinese Enterprises. *Economic Research Journal. 55*, 33-48.

[10] Atanassov J., Liu X., (2020). Can Corporate Income Tax Cuts Stimulate Innovation. *Journal of Financial and Quantitative Analysis. 55*, 1415~1465.

[11] Blind K., Petersen S. S., Riillo C. A. F., (2017). The Impact of Standards and Regulation on Innovation in Uncertain Markets. *Research Policy. 46*, 249~264.

[12] China Academy of Information and Communications Technology., (2021). White Paper on China's Digital Economy (2021). China Academy of Information and Communications Technology.

[13] Yang G. C., Liu J., Lian P., Rui M., (2017). Tax-Areducing Incentives, R&D Manipulation and R&D Performance. *Economic Research Journal. 52*, 110-124.

[14] Belloc F., (2021). Corporate Governance and Innovation: A Survey. *Journal of Economic Surveys. 26*, 835~864.

[15] Wang X. L., Hu L. P., Fan G., (2021). Marketization Index of China's Provinces: Neri Report 2021. Social Sciences Academic Press(China).

[16] Hsu P. H., Tian X., Xu Y., (2014). Financial Development and Innovation: Cross-country Evidence. *Journal of Financial Economics. 112*, 116~135.