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Original Paper

Digital Economy and Innovation Efficiency of High-tech Enterprises—On the Moderating Effect of Business Environment

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Abstract

As the key driving force of digital-real integration, whether high-tech enterprises can seize the opportunity brought by digital economy and improve innovation efficiency is of great significance to promote the optimization and upgrading of industrial structure and achieve high-quality economic development. Based on the data of China's digital economy and listed high-tech enterprises from 2015 to 2022, this paper discusses the impact of digital economy on the innovation efficiency of high-tech enterprises and its mechanism. We find that digital economy has a significant effect on the innovation efficiency of high-tech enterprises, and this conclusion is still valid after a series of robustness tests. Heterogeneity analysis shows that the digital economy has a more significant effect on improving the innovation efficiency of high-tech enterprises in non-state-owned, competitive industries and the eastern region. Mechanism analysis shows that digital economy can improve the innovation efficiency of high-tech enterprises by reducing enterprise costs and optimizing resource allocation. Finally, using the moderating effect model, we find that business environment plays a positive moderating role in the relationship between digital economy and innovation efficiency of high-tech enterprises.

Keywords

digital economy, high-tech enterprises, innovation efficiency, enterprise cost, resource allocation, business environment

1. Research Questions and Literature Review

The deep integration of digital economy and real economy is gradually changing the innovation activities of enterprises. In recent years, with the rapid iteration and extensive penetration of Internet technology,

big data analysis, cloud computing services, artificial intelligence technology and blockchain application, the vigorous development of digital economy has become the core force and important trend driving a new wave of scientific and technological revolution and promoting the deep transformation of global industry. At the same time, the combination of data elements and traditional production factors has promoted the accelerated integration of digital economy and real economy, provided more new ideas and resources for innovation, exerted various influences on enterprise innovation, effectively promoted the connection between innovation elements, innovation subjects and innovation links, and improved the innovation ability and efficiency of enterprises. New forms of business, new models and new products are constantly emerging. Obviously, digital economy has become the main trend of China's economic development, and high-tech enterprises, as the backbone of promoting the integration of data and reality, clarify the influence mechanism of digital economy development on the innovation efficiency of high-tech enterprises, so as to provide theoretical explanation and empirical support for digital economy to promote high-quality economic development from the perspective of improving enterprise innovation efficiency. In the current is of important theoretical significance and policy value. From the single perspective of digital technology affecting enterprise innovation, the continuous breakthrough of digital technologies such as big data, cloud computing and Internet has accelerated the speed of information dissemination, expanded the scope of information dissemination (Andres L et al., 2017), reduced the cost of information search for enterprises (Hoenig D et al., 2015), and strengthened the spillover effect of technology and knowledge. It expands the channels for enterprises to obtain innovative knowledge and technical information (Yoo Y J et al., 2010), and provides new ideas for enterprises to carry out innovation activities. It improves the transparency of market information, alleviates the problem of information asymmetry, promotes the communication between consumers and enterprises, and enables enterprises to accurately grasp the needs of consumers (Johnson J S et al., 2017), thus reducing the uncertainty of innovation (Cardinal L B et al., 2001) and improving the willingness of enterprises to innovate. In addition, some scholars have found that digital technology can optimize the innovation process of enterprises, shorten the innovation cycle, improve the operation efficiency of enterprises, thus reducing the R&D cost of enterprises (Tan K H et al., 2017), and promote enterprise innovation. From the comprehensive perspective that the development of digital economy affects enterprise innovation, most scholars believe that the development of digital economy promotes enterprise innovation, and discuss its influencing mechanism. Studies have found that digital economy can alleviate financing constraints (Yang S., 2024) and optimize human capital structure (Ya B et al., 2024), increasing R&D investment (Ling H & Ling X., 2025; Huang C, 2024), reducing corporate leverage (Hung C L & Chen M C, 2025), improving the quality of corporate information disclosure (Liu H et al., 2022), improving the degree of collaborative innovation (Xie X & Wang M, 2025) and enhancing corporate technology absorptive capacity (Peiyao Q & Runze Z, 2024), precipitation redundancy expansion effect, increasing patent return rate, changing enterprise organization mode, knowledge field activity and other mechanisms to promote

enterprise innovation (Jingling L et al., 2023; Jie L et al., 2023; Yang J et al., 2023; Lu S & Yanwen W, 2022).

In short, many scholars have made outstanding contributions to the research field of digital economy and enterprise innovation, but there are few studies focusing on digital economy and high-tech enterprise innovation, and few scholars have explored the impact of digital economy on high-tech enterprise innovation from the perspective of innovation efficiency. Based on this, the possible marginal contributions of this paper are as follows: Firstly, this paper examines the impact of digital economy on innovation efficiency of high-tech enterprises from a comprehensive perspective, and incorporates business environment into the analysis framework to verify its moderating effect on the relationship between digital economy and innovation efficiency of high-tech enterprises, which not only strengthens the empirical basis of digital economy influencing enterprise innovation efficiency, but also expands the theoretical boundary of its influencing mechanism. Second, this paper analyzes the different impacts of high-tech enterprises with different ownership structures, industries and geographical distribution on innovation efficiency under the background of digital economy, aiming to provide certain theoretical support and decision-making reference for local governments to formulate differentiated digital economic development strategies according to the unique attributes of high-tech enterprises.

2. Theoretical Mechanism and Research Hypothesis

2.1 Direct Effect of Digital Economy on Innovation Efficiency of High-tech Enterprises

The vigorous development of digital economy has opened up a new way for the improvement of innovation efficiency of high-tech enterprises. From the perspective of supply, the wide application of digital technology has continuously promoted the transformation of production mode of high-tech enterprises, enabling them to adopt advanced production technologies and processes. For example, the introduction of digital infrastructure such as intelligent manufacturing and industrial Internet can enable high-tech enterprises to realize the automation and intelligence of production processes, thus reducing the amount of R&D labor, greatly reducing R&D costs, improving production efficiency and product quality, and increasing innovation output. In addition, the factors of production supplier and the purchaser can use digital platform, big data and cloud computing services such as information technology for supply and demand information in time, to a certain extent break the barrier of the factor of information between supply and demand, thereby reducing the transaction cost, breadth and broaden the production elements and resource allocation, improve factor allocation distortion (Qin S et al., 2025). The sharing of digital platforms can also effectively reduce the learning cost of enterprises and the communication cost of enterprises in the process of industry-university-research cooperation, improve the absorption and application of cutting-edge knowledge, improve the quality of industry-university-research cooperation, and thus improve the innovation efficiency (Shi C & Zhou L, 2024). From the perspective of demand, the rise of digital economy has broken traditional market barriers such as institutional and geographical barriers, promoted the accelerated cross-regional flow of information, technology and resources,

broadened the market boundary and enlarged the total demand. The expansion of demand encourages enterprises to improve innovation efficiency, so as to maintain market competitive advantages and obtain higher profits. In addition, the popularity of digital technology enables enterprises to capture market information in real time, conduct efficient analysis and in-depth mining, accurately grasp the pulse of market demand, and predict the potential trend of demand, thus promoting the transformation of enterprise innovation mode from experience oriented to demand oriented. At the same time, consumers can use digital platforms not only to express their personalized needs, but also to actively participate in the process of product design and development, while enterprises can explore and analyze customer needs at a lower cost through digital technology enterprises, and provide personalized customized services (Hao D, 2024), which can reduce the uncertainty of enterprise innovation and improve innovation efficiency.

H1: Digital economy has a significant effect on the innovation efficiency of high-tech enterprises.

2.2 Corporate Cost Reduction Effect

The wide application of big data, Internet, block chain and other digital technologies enables high-tech enterprises to efficiently and accurately screen the required information from massive data, dig into the value of data, and accurately grasp the pulse of market demand, thus significantly reducing the cost of information collection and decision-making in the process of innovation. Further, the accelerated flow of information promotes the communication and interaction between and within enterprises, broadens the path of technology and knowledge dissemination, reduces the threshold for enterprises to obtain cutting-edge technology and knowledge, stimulates the innovation vitality of enterprises, and enhances the possibility of cooperation and innovation between enterprises, universities and research institutions, thus improving the overall innovation efficiency. In addition, high-tech enterprises can realize the digitalization of supply chain management through the introduction of digital technology, use intelligent management system for real-time monitoring and prediction analysis, reduce the idle and waste of resources, reduce logistics costs and inventory costs, so as to save more funds into innovation activities, improve innovation efficiency. At the same time, the continuous progress of digital technology promotes the improvement of enterprise management system day by day, effectively reduces the cost of internal and external communication, and promotes the transformation of enterprise organization structure from the traditional pyramid to network and flat. The digitalization of human resources management realizes the fine management of talents, and carries out efficient recruitment and training according to the analysis results of human resources system big data. Improve the efficiency of enterprise human resource management, reduce the cost of management and operation. Finally, advanced technologies such as digital twin and digital simulation can accurately map and reconstruct the physical world in the virtual environment, providing a space for high-tech enterprises to try innovation and iterated optimization in the digital field. This feature enables enterprises to select the best innovation plan through simulation test without increasing the actual cost. It can effectively reduce the cost of trial and error in the process of innovation and improve the efficiency of innovation.

H2: Digital economy can improve the innovation efficiency of high-tech enterprises by reducing enterprise costs.

2.3 Optimization Effect of Resource Allocation

The core of improving the innovation efficiency of high-tech enterprises lies in the efficient allocation of R&D capital, knowledge stock and entrepreneurship, so as to avoid idle and inefficient utilization of resources, which is a common challenge faced by many enterprises. The misallocation of resources often leads to the rise of innovation costs and weakens the enthusiasm of enterprises for innovation. However, the rapid development of digital economy has opened up new ways to solve this intractable problem. With the continuous improvement of digital infrastructure and the extensive and in-depth application of digital technology, enterprises can gradually allocate key innovation resources such as capital, talent and knowledge to the most needed places efficiently and accurately, effectively alleviate the problem of resource misallocation and idleness, and significantly improve the efficiency of resource use. In particular, the allocation capability of digital technology crosses the boundaries of time and space, promotes the free flow and optimal allocation of resources in different regions and enterprises, and maximizes the value of resources. As the cornerstone of innovation activities, R&D capital covers two parts: R&D capital investment and human capital. In view of the high risk and high investment characteristics of innovation activities, especially small and medium-sized enterprises often face financing problems. Digital economy promotes the development of inclusive finance, which not only broadens the boundary of financial services, but also greatly improves the availability of financial services and opens up diversified financing channels for enterprises. In addition, the deep integration and application of the Internet, big data and other technologies continue to optimize the evaluation mechanism of enterprise credit, effectively alleviate the information asymmetry between capital supply and demand, so that financial institutions can make decisions based on more accurate information and reduce credit risks. At the same time, enterprises can also use digital platforms to raise funds needed for innovation in a timely manner, which greatly alleviates financing problems and ensures that innovation activities are not restricted by the lack of funds. From the perspective of internal management, digital transformation accelerates the instant transmission of information, enabling management to make more rational innovation decisions based on comprehensive and timely data, so as to ensure accurate allocation of resources and maximize benefits. In terms of R&D human resources, digital economy has broken the regional boundaries and promoted the cross-regional flow and agglomeration effect of R&D talents. The improvement of information sharing platform promotes the best match between positions and talents, allows R&D personnel to provide R&D guidance for multiple enterprises through online means, realizes the efficient allocation of R&D human capital, and further improves the innovation efficiency of enterprises.

H3: Digital economy can improve the innovation efficiency of high-tech enterprises by optimizing the allocation of resources.

2.4 Moderating Effect of Business Environment

As a complex integration of policies, systems, rules and other elements, the business environment is a comprehensive development environment faced by enterprises in the whole process of activities, and a key link for enterprises to improve innovation efficiency (Yang T & Zhang C, 2025). A good business environment can enhance the improvement effect of digital economy on the innovation efficiency of high-tech enterprises. First of all, a good business environment can provide a fair and competitive market environment for high-tech enterprises, so that enterprises can reduce financing costs, improve resource allocation efficiency, spend more funds on the introduction of digital technologies and the construction of digital platforms, improve the level of collaborative innovation of various market players, accelerate the pace of digital transformation of enterprises, and enhance the spillover effect of knowledge and technology. To form a good innovation environment and improve innovation efficiency. Secondly, a good business environment can provide an efficient and clean government environment for high-tech enterprises. An open and transparent government can reduce the frequency of non-productive rent-seeking activities of enterprises, alleviate the problem of market information asymmetry, save institutional transaction costs, and guide enterprises to increase innovation investment and output (Enji L et al., 2023). At the same time, efficient administration can simplify the approval process for enterprises to carry out innovation activities, enable enterprises to obtain innovation resources in time, make rapid and accurate response to market demand, improve the market conversion rate of innovation results, and stimulate enterprises' willingness to innovate. Thirdly, a good business environment can provide a fair and transparent legal environment for high-tech enterprises. A sound legal system, intellectual property protection system and innovation policy can guarantee the standardized development of digital economy, safeguard the legal rights of enterprises, encourage enterprises to actively carry out innovation activities, increase R&D investment, and improve innovation efficiency. Finally, a good business environment provides an open and inclusive humanistic environment for high-tech enterprises. The introduction of digital technology and the construction of digital platform usually require a lot of investment and high risks. However, an open humanistic environment can solve the capital problem by attracting more foreign investment, reduce the trial and error cost of entrepreneurs through its high fault tolerance, and cultivate entrepreneurship. The open humanistic environment can solve the capital problem by attracting more foreign investment, reduce the trial and error cost of entrepreneurs through its high fault tolerance, and cultivate entrepreneurship. In short, a good business environment will attract more digital industrial agglomeration, accelerate the development of digital economy, produce scale effect, strengthen the spillover effect of knowledge and technology, and improve the innovation efficiency of enterprises.

H4: The optimization of business environment plays a positive role in the process of digital economy affecting the innovation efficiency of high-tech enterprises.

3. Research Design

3.1 Model Establishment

3.1.1 Benchmark Regression Model

In order to verify H1, that digital economy has a promotion effect on the innovation efficiency of high-tech enterprises, a two-way fixed effect model is established, and the specific regression equation is as follows:

$$EFF_{it} = \alpha_0 + \alpha_1 DIG_{pt} + \theta_1 \text{Control}_{it} + \theta_2 Control_{pt} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

Where i represents the enterprise, p represents the province, t represents the year, the explained variable EFF_{it} represents the innovation efficiency of high-tech enterprises, the explanatory variable DIG_{pt} is the Digital Economy Development Index,Control_{it} represents control variables at the enterprise level, $Control_{pt}$ represents control variables at the regional level, μ_i represents the individual fixed effect of the enterprise, δ_t represents the fixed effect of the year, and ε_{it} represents the random error term.

3.1.2 Mechanism Testing Model

The following mechanism test model is constructed to test the mechanism of digital economy affecting the innovation efficiency of high-tech enterprises:

$$\text{COST}_{it} = \alpha_0 + \alpha_1 DIG_{pt} + \theta_1 \text{Control}_{it} + \theta_2 Control_{pt} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

$$\text{REOP}_{it} = \alpha_0 + \alpha_1 DIG_{pt} + \theta_1 \text{Control}_{it} + \theta_2 Control_{pt} + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

Where COST_{it} represents the mechanism variable enterprise cost, REOP_{it} represents the mechanism variable enterprise resource allocation index to be tested, and the rest of the variables have the same meaning as Equation (1).

3.1.3 Moderating Effect Model

This paper constructs a moderating effect model to test the moderating role of business environment in the relationship between digital economy and innovation efficiency of high-tech enterprises.

$$EFF_{it} = \alpha_0 + \alpha_1 DIG_{pt} + \alpha_3 DIG_{pt} \times \text{BE}_{pt} + \theta_1 \text{Control}_{it} + \theta_2 Control_{pt} + \mu_i + \delta_t + \varepsilon_{it} \quad (4)$$

Where BE_{pt} represents the moderating variable business environment, and the interaction term $DIG_{pt} \times \text{BE}_{pt}$ represents the moderating effect of business environment; α_3 is the parameter to be estimated; if it is significantly positive, it means that the business environment has a positive moderating effect; if it is significantly negative, it means that the business environment has a negative moderating effect; the remaining variables have the same meaning as Equation (1).

3.2 Selection and Description of Variables

3.2.1 Explained Variable

There are three common methods to measure the innovation efficiency of high-tech enterprises: one is DEA (Concepción R et al., 2022; Vassilis K & Kostas T, 2022; Lee J et al., 2019); The second is stochastic frontier analysis SFA (Charnes A et al., 1978; Araujo T et al., 2007; Chen L et al., 2024); Third, direct calculation method. The core advantage of DEA method is that it does not need to preset the function form and estimate the parameters, so as to avoid the measurement bias caused by the improper setting of the production function, and can accurately evaluate the relative effectiveness of each decision-making

unit under the situation of multi-input and multi-output. This paper, therefore, using DEA method to measure efficiency of high and new technology enterprise innovation, innovation input variable is a high and new technology enterprise R&D investment in research and development personnel quantity and amount, innovation output variable is the enterprise patent number and the operating revenue, will measure innovation efficiency of data input DEAP software, the data is obtained from the CSMAR Database and the China Research Data Services Platform (CNRDS).

3.2.2 Core Explanatory Variables

The digital economy serves as the core explanatory variable in this study. Its measurement primarily follows two approaches: first, quantifying the absolute scale of the digital economy by statistically estimating its aggregate value within a defined geographic or sectoral scope (Roman C & Tatiana C, 2021; Yanmei Z & Yixin Z, 2022); second, assessing the relative level of the digital economy through a multidimensional indicator system that captures its conceptual breadth, such as composite indices evaluating digital infrastructure, industrial development, and enterprise adoption (Akberdina V et al., 2024; Hou J & Fu Y, 2024; Wang B & Wang J, 2025). To address data availability constraints, this study constructs a digital economy development index system from three dimensions—digital infrastructure, digital industry development level, and digital enterprise application level—and employs the entropy method to calculate the composite index (See Table 1).

Table 1. Evaluation System of Digital Economy Development

First-level indicators	Secondary indicators	Tertiary indicators
Digital infrastructure	Traditional infrastructure	Number of Internet broadband access ports (ten thousand)
		Number of Internet broadband access users (ten thousand)
		Number of domain names per 1,000 people (10,000)
		Number of web pages per thousand people (10,000)
	New digital infrastructure	Mobile phone penetration rate (units / 100 people)
		Number of mobile phone base stations (ten thousand)
		Number of IPV4 addresses (10,000)
Level of digital industry development	Scale of the communications industry	Total amount of telecommunications business (100 million yuan)
	Software and information technology services	Revenue from software business (100 million yuan)
		Revenue from software products (RMB ‘000)

Level of digital enterprise application		Revenue from information technology services (RMB 100 million)
	Digital finance	Digital Financial Inclusion Index
	Enterprise information network level	Number of computers used per 100 people in an enterprise (units)
		Number of websites per 100 businesses (units)
	Level of enterprise e-commerce	Proportion of enterprises with e-commerce transaction activities (%)
		Enterprise e-commerce sales (100 million yuan)

3.2.3 Control Variables

Based on the existing research, the following control variables are selected from the enterprise level and the regional level: enterprise size (size) is represented by the logarithm of the total assets of the enterprise; Asset-liability ratio (loar); Current ratio (cr); Capital intensity (capi) is expressed by the logarithm of net fixed assets divided by the number of employees; Industrial structure (stru) is measured by the ratio of the output value of the tertiary industry to the secondary industry in a region; Government support for science and technology (gove) is measured by the proportion of government funds in internal R&D expenditure; Gross regional product (gdp).

3.2.4 Mechanism Variables

The enterprise COST (COST) is used as the mechanism variable, and the ratio of the enterprise management expense to the total assets of the enterprise is used to measure. The decrease of enterprise cost indicates that the digital economy can improve the innovation efficiency of high-tech enterprises by reducing enterprise cost. The optimization of resource allocation can reduce idle resources, avoid the waste of resources to a certain extent, and improve the utilization rate of resources, so as to improve the innovation efficiency of high-tech enterprises. The deviation degree of the four dimensions of enterprise strategic resource allocation from its own and the average level of the industry is selected as the measurement method of whether the resource allocation is improved. To construct the resource allocation index (REOP).

3.2.5 Moderating Variables

The business environment Index of Chinese Enterprises by Province in 2017 Report, the Business Environment Index of Chinese Enterprises by Province in 2020 Report and the Business Environment Index of Chinese Enterprises by Province in 2023 Report were collected in the sample period, and the missing data in some years were supplemented by linear interpolation method.

Table 2 reports the results of descriptive statistical analysis of variables. The mean value of innovation efficiency calculated by DEA method is 0.855, the minimum value is 0.654, the maximum value is 1, and the standard deviation is 0.055, indicating that there is still some room for improvement in the

innovation efficiency of China's high-tech enterprises. The mean value of digital economy development index is 0.214, the minimum value is 0.014, the maximum value is 0.864, and the standard deviation is 0.173, which indicates that the development of digital economy in China is still in the initial stage, and there are great differences in the development level of digital economy in different provinces and cities.

Table 2. Descriptive Statistics of Main Variables

Variables	Observations	Mean	SD.	Min	Max
EFF	6760	0.855	0.055	0.654	1
DIG	6760	0.214	0.173	0.014	0.864
COST	6760	0.044	0.027	-0.029	0.526
REOP	6760	-0.198	1.454	-6.858	15.621
BE	6760	3.707	0.136	3.19	3.92
size	6760	22.313	1.174	19.56	28.052
loar	6760	0.406	0.198	0.014	3.097
cr	6760	2.395	2.46	0.153	50.137
capi	6760	12.51	0.988	7.521	15.578
stru	6760	1.716	1.149	0.756	5.297
gove	6760	0.3	0.734	0.015	10.554
gdp	6760	10.788	0.648	7.79	11.769

3.3 Data Source

In order to ensure the comprehensiveness and credibility of the data, this study selected the high-tech enterprises listed in China's A-share market from 2015 to 2022 as the research samples, and carried out the following processing: In order to ensure the integrity of the data and the effectiveness of the analysis, we further excluded the samples of financial and insurance companies, specially treated ST companies, and companies with serious data missing. After the above processing, 845 listed high-tech enterprises are selected as the research samples, with a total of 6760 observed values. The relevant data of high-tech enterprises come from CSMAR database and China Research Data Service platform CNRDS. The relevant data of digital economy come from China Information Industry Yearbook, National Bureau of Statistics, China Torch Statistical Yearbook, Institute of Digital Finance of Peking University, China Statistical Yearbook, China Statistical Yearbook on Science and Technology, etc.

4. Empirical Analysis

4.1 Benchmark Regression Results

Table 3 shows the benchmark regression results of the impact of digital economy on the innovation efficiency of high-tech enterprises. Column (1) controls the time fixed effect, Column (2) controls the

time fixed effect and individual fixed effect, Column (3) adds the enterprise-level control variables, and Column (4) adds the region-level control variables. All the models pass the significance test, and the regression coefficients of digital economy are significantly positive at the level of 1%, indicating that digital economy is indeed conducive to the improvement of innovation efficiency of high-tech enterprises, and Hypothesis 1 is proved.

Table 3. The Benchmark Regression Results

	(1)	(2)	(3)	(4)
	EFF	EFF	EFF	EFF
DIG	0.0097***	0.0105***	0.0106***	0.0095***
	(0.0030)	(0.0031)	(0.0024)	(0.0025)
size			-0.0364***	-0.0364***
			(0.0006)	(0.0006)
loar			0.0079***	0.0081***
			(0.0020)	(0.0020)
cr			0.0010***	0.0010***
			(0.0001)	(0.0001)
capi			0.0046***	0.0046***
			(0.0005)	(0.0005)
stru				0.0023**
				(0.0011)
gove				0.0000
				(0.0003)
gdp				0.0019
				(0.0027)
cons	0.8707***	0.8706***	1.6046***	1.5808***
	(0.0019)	(0.0007)	(0.0133)	(0.0313)
Id	Yes	Yes	Yes	Yes
Year	No	Yes	Yes	Yes
N	6760	6760	6760	6760
R^2	0.398	0.398	0.650	0.650

Note. ***p < 0.01, **p < 0.05, *p < 0.1. Standard errors of coefficients are reported in parentheses.

4.2 Discussion on Endogeneity

The impact of digital economy on the innovation efficiency of high-tech enterprises has endogenous problems. The main reason is that listed high-tech enterprises usually have a large scale, which has a

certain impact on the development of digital economy in the registered area. Moreover, enterprises with high innovation efficiency generally have a high level of digitalization. Therefore, the innovation efficiency of listed high-tech enterprises may negatively affect the development level of digital economy in a province or city. To address endogeneity concerns stemming from bidirectional causality, we construct an instrumental variable by multiplying the cross-sectional data on provincial terrain ruggedness with the number of internet broadband subscribers in the same year, following the approach of Nunn et al., (2014), and employs a two-stage least squares (2SLS) regression methodology, with the regression results presented in Table 4. A two-stage least squares (2SLS) regression is implemented, with the estimation results reported in Table 4. The first-stage regression results show that the digital economy is significantly negatively correlated with the instrumental variable, indicating that the greater the terrain relief is, the slower the development level of the digital economy is, because the development of the digital economy cannot be separated from the construction of infrastructure. The second stage regression results show that the digital economy of high and new technology enterprise innovation efficiency has significant effect, while LM statistics and Wald F statistic shows that there is no shortage problem of weak instrumental variable and recognition, the two-stage least squares (2SLS) estimates align with our theoretical predictions, thereby reinforcing the credibility of the study's causal conclusions.

Table 4. Regression Results of Endogeneity Test

	(1)	(2)
	DIG	EFF
IV1	-0.1154***	
	(0.01060)	
DIG		0.0776***
		(0.0195)
size	0.0118***	-0.0362***
	(0.0035)	(0.0007)
loar	0.0402***	0.0014
	(0.0123)	(0.0027)
cr	0.0017**	0.0006***
	(0.0008)	(0.0002)
capi	0.0053*	0.0038***
	(0.0029)	(0.0006)
stru	0.0084	0.0041***
	(0.0063)	(0.0013)
gove	0.0426***	-0.0035***
	(0.0017)	(0.0009)

gdp	0.5519***	-0.0608***
	(0.0130)	(0.0087)
Year	Yes	Yes
Id	Yes	Yes
N	6760	6760
R^2		0.400
LM statistic		116.298***
Wald F statistic		118.471***

Note. ***p < 0.01, **p < 0.05, *p < 0.1. Standard errors of coefficients are reported in parentheses.

4.3 Test for Robustness

To ensure the robustness of our findings, this study conducts robustness tests from three perspectives. First, we replace the core explanatory variable by employing its one-period lagged term (DIG1) as the independent variable. The regression results, reported in column (1) of Table 5, show that the coefficient of the lagged digital economy (DIG1) is 0.0133 and statistically significant at the 1% level. Second, to mitigate potential bias in measuring innovation efficiency of high-tech firms, we substitute the dependent variable with the natural logarithm ratio of patent grants to R&D expenditure. As shown in column (2) of Table 5, the coefficient of the digital economy remains statistically significant at the 1% level. Third, to address model selection bias, we re-estimate the regression using a high-dimensional fixed effects model. The results in column (3) of Table 5 indicate that the digital economy's coefficient is 0.0095, significant at the 1% level, with no change in sign. All robustness test outcomes confirm the statistical significance of our baseline results, further supporting the reliability of the conclusions.

Table 5. Robustness Test

	(1)	（2）	(3)
	EFF	EFF1	EFF(the high-dimensional fixed effect model)
DIG1	0.0133***		
	(0.0037)		
DIG		7.3517***	0.0095**
		(1.1310)	(0.0039)
size	-0.0376***	3.0795***	-0.0364***
	(0.0006)	(0.2630)	(0.0013)
loar	0.0101***	-2.2402**	0.0081
	(0.0022)	(0.9165)	(0.0057)
cr	0.0011***	0.1005*	0.0010***

	(0.0001)	(0.0562)	(0.0004)
capi	0.0046***	0.0842	0.0046***
	(0.0005)	(0.2115)	(0.0009)
stru	0.0019	1.5831***	0.0023
	(0.0013)	(0.5211)	(0.0016)
gove	-0.0001	0.0516	0.0000
	(0.0003)	(0.1391)	(0.0003)
gdp	0.0005	-0.3660	0.0019
	(0.0031)	(1.2288)	(0.0051)
cons	1.6150***	-64.1543***	1.5768***
	(0.0368)	(14.2810)	(0.0642)
Year	Yes	Yes	Yes
Id	Yes	Yes	Yes
N	5915	6760	6760
R^2	0.642	0.088	0.945

Note. ***p < 0.01, **p < 0.05, *p < 0.1. Standard errors of coefficients are reported in parentheses.

4.4 Test for Heterogeneity

4.4.1 The Enterprise Heterogeneity Analysis

As the main body of innovation activities, the innovation efficiency of high-tech enterprises is not only related to the external environment, but also related to their own characteristics. Therefore, in order to explore the differentiated impact of digital economy on the innovation efficiency of high-tech enterprises, this paper divides all samples into two groups according to the ownership nature of enterprises: state-owned enterprises and non-state-owned enterprises, and conducts regression respectively. The results are shown in Columns (1) and (2) of Table 6. Among them, Column (1) shows that the coefficient of digital economy on the innovation efficiency of state-owned high-tech enterprises is 0.0076, which is significantly positive at the level of 10%. Column (2) shows that the coefficient of digital economy on the innovation efficiency of non-state-owned high-tech enterprises is 0.0088, which is significantly positive at the level of 1%. It shows that the digital economy has a more significant impact on the innovation efficiency of non-state-owned high-tech enterprises. The main reason is that non-state-owned high-tech enterprises are more flexible. In the face of the opportunities and challenges brought by the digital economy, they can more flexibly adjust their innovation strategies, actively introduce digital technologies, and improve innovation efficiency. At the same time, non-state-owned high-tech enterprises are faced with greater pressure of market competition. In order to maintain their core advantages in the fierce market competition, they must constantly improve their innovation ability.

4.4.2 Industry Heterogeneity Analysis

For enterprises in different industries, is there a heterogeneous impact of the development of digital economy on their innovation efficiency? In order to explore this question, all enterprise samples are divided into two groups: enterprises in regulated industries and enterprises in competitive industries, and the results are shown in Columns (3) and (4) of Table 6. Column (3) shows that in competitive industries, the regression coefficient of digital economy is 0.0103, which is significantly positive at the level of 1%. Column (4) shows that in regulated industries, the regression coefficient of digital economy is not significant, indicating that the development of digital economy has a more significant impact on the innovation efficiency of high-tech enterprises in competitive industries. To control the effect of high and new technology enterprise innovation efficiency in the sex industry is not obvious. The reason is that market demand changes rapidly, and enterprises in competitive industries must assess the situation, accurately judge the changes in market demand, and improve innovation efficiency to maintain core competitive advantages by grasping the opportunities brought by digital economy.

Table 6. Heterogeneity Test Based on Firm Differences and Industries

	(1) state-owned enterprise	(2) Non-state-owned enterprise	(3) Competitive industry	(4) Non-competitive industry
DIG	0.0076*	0.0088***	0.0103***	0.0072
	(0.0041)	(0.0031)	(0.0026)	(0.0077)
size	-0.0317***	-0.0374***	-0.0366***	-0.0355***
	(0.0013)	(0.0007)	(0.0006)	(0.0018)
loar	-0.0023	0.0083***	0.0082***	0.0082
	(0.0051)	(0.0022)	(0.0021)	(0.0076)
cr	0.0008*	0.0010***	0.0010***	0.0005
	(0.0005)	(0.0001)	(0.0001)	(0.0007)
capi	0.0044***	0.0047***	0.0050***	0.0018
	(0.0011)	(0.0005)	(0.0005)	(0.0016)
stru	0.0030	0.0022	0.0013	0.0071**
	(0.0019)	(0.0014)	(0.0012)	(0.0033)
gove	-0.0001	0.0002	-0.0001	0.0002
	(0.0004)	(0.0004)	(0.0003)	(0.0008)
gdp	0.0056	-0.0004	-0.0006	0.0146*
	(0.0041)	(0.0035)	(0.0028)	(0.0083)
cons	1.4387***	1.6277***	1.6087***	1.4590***
	(0.0535)	(0.0397)	(0.0327)	(0.0986)

Year	Yes	Yes	Yes	Yes
Id	Yes	Yes	Yes	Yes
N	1848	4896	5832	928
R^2	0.652	0.651	0.672	0.526

Note. ***p < 0.01, **p < 0.05, *p < 0.1. Standard errors of coefficients are reported in parentheses.

4.4.3 Regional Heterogeneity Analysis

Due to the different resource endowments in different regions, there are regional differences in the development of digital economy. All sample enterprises are divided into four groups: eastern, central, western and northeastern, and regression is conducted respectively to explore the difference in the impact of digital economy on the innovation efficiency of high-tech enterprises in different regions (see Table 7). The coefficient of digital economy in the eastern region is 0.0135, which is significant at the level of 1%, indicating that the digital economy has a significantly positive impact on the innovation efficiency of high-tech enterprises in the eastern region. The coefficient of digital economy in the western region is − 0.0842, which is negative at the significance level of 10%, indicating that digital economy has a negative impact on the innovation efficiency of high-tech enterprises in the western region. The estimated coefficient of digital economy in the central and northeastern regions is not significant, indicating that the digital economy has no significant impact on the innovation efficiency of high-tech enterprises in the central and northeastern regions. The reason is that the eastern region has the first-step advantage in the development of digital economy, the infrastructure is more perfect than other regions, and many high-quality and high-tech talents, capital and innovation resources are gathered nationwide, which makes the knowledge and technology spillover effect stronger and the level of digital economy development higher. Meanwhile, the integration of digital economy and traditional industries in the eastern region has been deeper. This is conducive to the improvement of innovation efficiency of high-tech enterprises in the eastern region. However, the level of digital infrastructure in central China is low, and the development of digital economy is still in the initial stage, which has a large late-comer advantage and a rapid growth momentum. Due to the weak infrastructure construction, low level of economic development and serious brain drain in the western region, the high cost of digital transformation makes enterprises bear a heavy burden, which hinders the improvement of enterprise innovation efficiency to a certain extent. The northeast region only includes Liaoning, Jilin and Heilongjiang provinces, whose digital economy development level is low, so its improvement effect on the innovation efficiency of high-tech enterprises is not significant.

Table 7. Heterogeneity Test Based on Regional Differences

	(1) East	(2) Central	(3) West	(4) Northeast
DIG	0.0135***	0.1086	-0.0842*	0.2200
	(0.0037)	(0.0775)	(0.0446)	(0.2414)
size	-0.0359***	-0.0309***	-0.0404***	-0.0462***
	(0.0007)	(0.0017)	(0.0018)	(0.0054)
loar	0.0133***	-0.0054	-0.0071	0.0132
	(0.0023)	(0.0059)	(0.0068)	(0.0131)
cr	0.0015***	0.0006	0.0010	-0.0002
	(0.0002)	(0.0004)	(0.0007)	(0.0004)
capi	0.0048***	0.0051***	0.0079***	0.0052
	(0.0005)	(0.0013)	(0.0023)	(0.0041)
stru	0.0023*	-0.0036	0.0137	0.0096
	(0.0013)	(0.0050)	(0.0096)	(0.0093)
gove	-0.0002	0.0007	-0.0002	-0.0124
	(0.0005)	(0.0015)	(0.0006)	(0.0152)
gdp	0.0051	-0.0008	0.0064	-0.0141
	(0.0037)	(0.0101)	(0.0146)	(0.0246)
cons	1.5270***	1.4878***	1.5919***	1.9546***
	(0.0432)	(0.1084)	(0.1480)	(0.2707)
Year	Yes	Yes	Yes	Yes
Id	Yes	Yes	Yes	Yes
N	5000	1072	456	232
R^2	0.660	0.639	0.718	0.500

Note. ***p < 0.01, **p < 0.05, *p < 0.1. Standard errors of coefficients are reported in parentheses.

5. Analysis of Influencing Mechanism

5.1 Test of Influence Mechanism

According to Formula (2), the cost reduction effect of enterprises is tested, and the results are shown in Column (1) of Table 8. The coefficient of digital economy is − 0.0101, which is significantly negative at the level of 1%, indicating that the development of digital economy can reduce the cost of high-tech enterprises, and the reduction of enterprise cost is conducive to the improvement of innovation efficiency. H 2 is proved. According to Formula (3), the optimization effect of resource allocation is tested, and the results are shown in Column (2) of Table 8. The coefficient of digital economy is 0.4767, which is significantly positive at the level of 5%, indicating that digital economy can promote the optimization of

resource allocation of high-tech enterprises, and the development of digital economy can break the restrictions of time and space, and accelerate the free flow of resources. The development of digital economy can break the limitation of time and space and accelerate the free flow of resources.

5.2 Moderating Effect Test

The external environment of high-tech enterprises may moderate the impact of the digital economy on their innovation efficiency. To test this channel, we introduce a moderating variable—the business environment index—and construct an interaction term by demeaning both the digital economy index and the business environment index (to mitigate multicollinearity). Following Equation (4), the regression results reported in Column (3) of Table 8 show that: the interaction term between the digital economy and the business environment index has a statistically significant positive effect on innovation efficiency at the 1% level (coefficient = 0.0301), and the standalone coefficient of the digital economy remains significantly positive at the 1% level (coefficient = 0.008). This indicates that an improved business environment amplifies the innovation-enhancing effect of the digital economy, thereby validating H4.

Table 8. Mechanism Test and Moderating Effect Test

	(1)	(2)	(3)
	COST	REOP	EFF
DIG	-0.0101***	0.4767**	0.0080***
	(0.0027)	(0.2270)	(0.0025)
DIG×BE			0.0301***
			(0.0110)
size	-0.0204***	-0.0113	-0.0360***
	(0.0006)	(0.0528)	(0.0006)
loar	0.0258***	0.7617***	0.0020
	(0.0022)	(0.1839)	(0.0021)
cr	-0.0006***	-0.0156	0.0009***
	(0.0001)	(0.0113)	(0.0001)
capi	-0.0025***	0.7798***	0.0045***
	(0.0005)	(0.0424)	(0.0005)
stru	-0.0035***	0.0119	0.0028**
	(0.0012)	(0.1046)	(0.0011)
gove	0.0005	-0.0554**	0.0004
	(0.0003)	(0.0279)	(0.0003)
gdp	-0.0073**	0.0546	0.0017
	(0.0029)	(0.2466)	(0.0027)
cons	0.6103***	-10.3253***	1.5769***

	(0.0336)	(2.8662)	(0.0309)
Year	Yes	Yes	Yes
Id	Yes	Yes	Yes
N	6760	6760	6760
R^2	0.403	0.069	0.658

Note. ***p < 0.01, **p < 0.05, *p < 0.1. Standard errors of coefficients are reported in parentheses.

6. Conclusions and Implications

6.1 Conclusions

The improvement of innovation efficiency of high-tech enterprises is not only conducive to improving their competitiveness and profitability, but also conducive to promoting the optimization and upgrading of industrial structure and promoting high-quality economic development. The vigorous development of digital economy can provide new ideas and new resources for high-tech enterprises to innovate, and provide more possibilities for the improvement of innovation efficiency of high-tech enterprises. Based on this, this paper selects panel data of China's digital economy and listed high-tech enterprises from 2015 to 2022 to empirically test the effect, heterogeneity and mechanism of digital economy on the innovation efficiency of high-tech enterprises, and draws the following conclusions: First, the development of digital economy is indeed conducive to the improvement of innovation efficiency of high-tech enterprises, and this conclusion is still valid after the endogeneity treatment and robustness test. Therefore, China should continue to develop the digital economy, give full play to the dividend of the digital economy, promote the deep integration of the digital economy and the real economy, and promote the high-quality development of enterprises. Second, from the perspective of enterprise heterogeneity, the digital economy has a more significant effect on improving the innovation efficiency of non-state-owned high-tech enterprises; From the perspective of industry heterogeneity, digital economy has a greater impact on the innovation efficiency of high-tech enterprises in competitive industries. From the perspective of regional heterogeneity, the digital economy has a significant effect on the innovation efficiency of high-tech enterprises in the eastern region, a negative effect on the innovation efficiency of high-tech enterprises in the western region, and no significant effect on the innovation efficiency of high-tech enterprises in the central and northeastern regions. Third, digital economy can improve the innovation efficiency of high-tech enterprises by reducing enterprise costs and optimizing resource allocation. Fourthly, a good business environment can strengthen the improvement effect of digital economy on the innovation efficiency of high-tech enterprises.

6.2 Policy Implications

Based on the above research conclusions, the following policy implications are drawn: First, the development of the digital economy to broaden the way of high technology and new technology enterprise innovation efficiency, therefore governments at all levels should continue to improve digital infrastructure construction, strengthen the core research and development, the application of digital

technology, endowment characteristics implement differentiation based on region economic development strategy, to narrow the gap in regional economic development, especially the construction of the digital infrastructure, to improve its Midwest Increase investment, improve the application and innovation level of digital technology, promote the coordinated development of regional digital, actively implement the "East and West computing" project and other strategies, accelerate the construction of national integrated computing power network, deepen the integration of computing network, strengthen network support, promote the interconnection of computing power, and effectively promote the sharing and optimal allocation of digital resources between regions. At the same time, we will encourage high-tech enterprises to make good use of digital platforms, actively introduce big data, artificial intelligence, cloud computing and other digital technologies to reduce the cost of innovation, optimize the allocation of innovation resources and optimize the innovation process, so as to improve innovation efficiency, promote the optimization and upgrading of industrial structure, and achieve high-quality economic development.

Second, when formulating relevant policies, we should pay attention to the endowment differences and external environment differences of high-tech enterprises. In terms of enterprise heterogeneity, for non-state-owned high-tech enterprises, the government should adopt certain preferential policies to help them carry out digital transformation, make breakthroughs in core technologies, and enhance their international competitiveness. In addition, due to the small scale of some non-state-owned high-tech enterprises, they often face more financing problems in the process of digital transformation. The government should give them certain financial support, strengthen the deep integration of digital technology and financial services, provide them with more convenient financial services, and lower the capital threshold for non-state-owned high-tech enterprises to introduce digital technology. Encourage enterprises to actively apply and innovate digital technology. For state-owned high-tech enterprises, the way to promote innovation efficiency mainly is to change its innovation incentive mechanism, to guide its independent innovation, enhance their sense of competition and innovation willingness to break the traditional mode of production and operation as well as the closed innovation model, and the different main body joint innovation, thus improve their innovation efficiency. In terms of industry heterogeneity, high-tech enterprises in regulated industries should be encouraged to actively introduce cloud computing, artificial intelligence and other digital technologies, so as to improve the competitive vitality of regulated industries and avoid monopoly behaviors caused by huge differences in innovation capabilities. For high-tech enterprises in competitive industries, they should continue to promote the process of digitalization, improve the efficiency of enterprise innovation, and promote the optimization and upgrading of the whole industry structure. In terms of regional heterogeneity, the primary solution is to solve the problem of unbalanced development of digital economy, increase investment in digital sharing platform, implement relevant policies and measures to encourage the eastern regions with developed computing power to drive the development of digital economy in the central and western regions, form a large pattern of coordinated development of regional digital economy, and eliminate the digital divide.

Third, building a good ecology of digital economy, business environment and enterprise innovation is conducive to the continuous improvement of innovation efficiency of high-tech enterprises. To improve the innovation efficiency of high-tech enterprises, we should not only seize the opportunities brought by the digital economy, but also promote the continuous optimization of the business environment, so as to enhance the improvement effect of digital economy on the innovation efficiency of high-tech enterprises. Under the background of digital economy, we should vigorously promote the construction of digital government and digital platform, establish a reasonable digital governance system, reduce non-productive rent-seeking activities, introduce digital technology to timely and accurately disclose enterprise information, improve the transparency of market information, and form a good competitive environment. Improve the legal system of intellectual property, create a good legal environment, protect the legitimate rights and interests of enterprises to innovate, so as to stimulate the innovation willingness of high-tech enterprises; Expand the application scope of digital technology, reduce the trial and error cost of enterprises, improve the fault tolerance rate of the market environment, form an inclusive human environment, cultivate more entrepreneurs who are brave to innovate, form a good market environment, government environment, legal environment and human environment, so as to strengthen the effect of digital economy on innovation efficiency and promote the high-quality development of high-tech enterprises.

Projects

1. The Impact and Mechanism of Market-Oriented Allocation of Data Elements on Enhancing the Resilience of Industrial and Supply Chains (LSKJ2025-019)
2. Exploration of the Path for Agricultural New-Quality Productive Forces to Empower the Comprehensive Rural Revitalization in Gansu (LSKJ2025-004)
3. Research on the Cultivation Effectiveness and Enhancement Strategies of "Specialized, Sophisticated, Distinctive, and Innovative" Enterprises in Northwest China (LSKJ2025-001)

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