

# The Impact of the Digital Economy on the Green Innovation Efficiency of the Manufacturing Industry

Ran Li

Anhui University of Finance and Economics, Bengbu 233030, China

## Abstract

The rapid expansion of the digital economy offers a new impetus for advancing green innovation efficiency within the manufacturing sector. Grounded in innovation ecosystem theory, this study employs panel data from 30 Chinese provinces (municipalities) spanning 2012 to 2022 to empirically examine the influence of the digital economy on the green innovation efficiency of manufacturing and its spatial spillover effects. The findings reveal that: (1) The digital economy substantially enhances green innovation efficiency in China's manufacturing industry, a conclusion that holds across multiple robustness checks, including substitution of explanatory and explained variables. This effect is more pronounced in provinces with higher economic development, advanced digital economy levels, and those not reliant on natural resources. (2) The digital economy fosters green innovation efficiency through three pathways: optimizing resource allocation efficiency, promoting technological progress, and upgrading industrial structure. Among these, industrial structure upgrading exhibits the strongest transmission effect, while resource allocation efficiency and technological progress show relatively smaller impacts. (3) Both the digital economy and manufacturing green innovation efficiency display notable spatial agglomeration traits and generate spatial spillover effects on neighboring regions, specifically manifesting as a "siphon effect." Industrial agglomeration further amplifies this siphon effect of the digital economy.

## Keywords

Digital Economy; Green Innovation Efficiency of the Manufacturing Industry; Innovation Ecosystem Theory; Spatial Spillover.

## 1. Introduction

As a strategic pillar industry for national economic development, manufacturing is not only the core field for technological innovation and industrial upgrading but also the fundamental guarantee for consolidating comprehensive national strength. According to data from the State Council Information Office, by 2024, China's total industrial added value will reach 40.5 trillion yuan, and the overall scale of the manufacturing industry will remain the world's largest for 15 consecutive years. The proportion of manufacturing added value in the world will jump from 5% in 1980 to 28.9% in 2024. However, behind this long-term rapid development lies an undeniable issue of energy consumption. According to the Statistical Bulletin on National Economic and Social Development of the People's Republic of China in 2023, the national energy consumption in 2023 reached 5.72 billion tons of standard coal, of which manufacturing energy consumption accounted for about two-thirds of the total, and carbon emissions accounted for about 70%. In February 2024, the Guiding Opinions of the Ministry of Industry and Information Technology and Seven Other Departments on Accelerating the Green Development of the Manufacturing Industry proposed main goals, including achieving significant results in the green and low-carbon transformation of the manufacturing industry, significantly increasing the proportion of green and low-carbon energy utilization, and peaking

total carbon emissions by 2030. Therefore, improving the green innovation efficiency of the manufacturing industry has become an urgent practical problem in China. It is not only an important path for high-quality development but also a practical requirement for achieving sustainable development and a crucial lever for China to achieve its "dual carbon" goals.

Currently, China's digital economy is entering a stage of rapid development. Statistics show that the scale of China's digital economy continued to expand in 2023, and its proportion in the Gross Domestic Product (GDP) climbed to 42.8%, an increase of 1.3 percentage points from the previous year. In terms of growth rate, the digital economy grew rapidly with a nominal growth rate of 7.39%, which was 2.76 percentage points higher than the GDP growth rate during the same period. Regarding its contribution to overall economic growth, its driving effect reached 66.45%, effectively supporting stable economic growth. Through technologies such as the Internet and cloud computing, the digital economy accelerates the codification and modularization of green innovation knowledge, significantly promoting the transformation of traditional production modes towards sustainable development models. The widespread and deep integration of the digital economy with the real economy serves as an important driving force for promoting higher-quality and more sustainable development of China's manufacturing industry. In the context of "dual carbon," has the digital economy become a key driver for promoting green innovation efficiency in the manufacturing industry? Can digital platforms break traditional geographical boundaries, promote the diffusion of green technologies across enterprises and industries, and impact the green innovation efficiency of surrounding areas through spillover effects?

## 2. Literature Review

Green innovation efficiency refers to the capacity within green innovation activities to holistically consider the environmental costs of innovation input and output processes, achieve efficient resource utilization, reduce environmental burdens, and enhance economic benefits through technological and managerial means [1]. Existing studies on green innovation efficiency in manufacturing predominantly focus on regional efficiency measurement and influencing factors. Liao assessed green innovation efficiency across Chinese cities, finding that while overall disparities are narrowing, spatial differentiation is deepening [2]. Zhang applied the super-efficiency SBM model to evaluate green innovation efficiency in 16 prefecture-level cities within the Comprehensive Experimental Zone for the Conversion of Old and New Kinetic Energy, revealing a spatial pattern of "high in the east and low in the west" [3]. Huang explored the spatiotemporal evolution of green innovation efficiency in resource-based cities, concluding that industrial structure upgrading can markedly improve urban green innovation efficiency [4]. Scholars also examine factors influencing green innovation efficiency from internal and external perspectives [5]. Regarding internal factors, Liu empirically analyzed the impact of digital transformation on the green innovation efficiency of manufacturing firms, finding that digital transformation significantly enhances such efficiency [6]. Li studied determinants of green innovation efficiency in construction enterprises, demonstrating through empirical tests that the industrial structure of the construction sector exerts a significant positive influence [7]. Peng investigated the effect of corporate ESG performance on green innovation efficiency, showing that robust ESG performance substantially improves corporate green innovation efficiency [8]. Concerning external factors, Ren explored the impact of climate risk on the green innovation efficiency of listed companies, concluding that climate risk enhances green innovation efficiency by raising public awareness of environmental performance [9]. Tian analyzed the influence of the Belt and Road Initiative on corporate green innovation efficiency, finding that the policy promotes such efficiency by fostering green entrepreneurship, cooperative innovation, and environmental investment [10]. Hu examined

the effect of carbon emission trading on the green innovation efficiency of industrial enterprises, indicating that its implementation aids enterprises in improving their green innovation efficiency [11].

### **3. Theoretical Analysis and Research Hypotheses**

#### **3.1. The Impact of Digital Economy on Green Innovation Efficiency in Manufacturing Industry**

According to the theory of new economic growth, the digital economy has the characteristics of increasing marginal returns of data elements and green knowledge spillover. These characteristics can reconstruct the green innovation production function of the manufacturing industry, enabling enterprises to break through traditional resource constraints and achieve clean transformation through precise energy consumption monitoring and process optimization. Firstly, a real-time monitoring system based on the Internet of Things and big data analysis can accurately track the energy consumption and emission data of the entire production process, driving enterprises to optimize their process flow and reduce resource waste. Secondly, artificial intelligence algorithms can quickly match green technology application scenarios through simulation and intelligent decision-making, including predictive maintenance to reduce equipment idle energy consumption and intelligent scheduling to optimize the proportion of clean energy use. Moreover, the industrial Internet platform breaks the information barriers of the industrial chain, promotes cross-enterprise sharing and collaborative R&D of green patented technologies and low-carbon solutions, and forms an innovation closed loop of "R&D-application-feedback." In addition, blockchain technology provides a trustworthy mechanism for carbon footprint tracing, incentivizing companies to obtain market premiums through green innovation. The deep integration of digital technology and green innovation not only reduces the trial-and-error costs of green transformation in the manufacturing industry but also constructs a win-win situation of total factor productivity improvement and ecological environment improvement through the restructuring of production factors and the transformation of innovation paradigms.

The promotion effect of the digital economy on green innovation efficiency may have regional heterogeneity, as well as heterogeneity based on economic development level, digital economy level, and resource endowment. Firstly, the eastern region, relying on a high degree of marketization and coordinated industrial chain improvement, makes it easier for digital technology to penetrate the production process. In contrast, the central and western regions are limited by lagging infrastructure and a lack of high-end talent, resulting in limited efficiency in the green empowerment of the digital economy. However, underdeveloped regions can achieve leapfrog development through technological imitation and policy support. Western provinces can skip the traditional industrialization stage, reduce path dependence, and unleash green innovation potential faster. Secondly, high-income provinces have strong fiscal capacity and R&D investment, which can support the integration of digital technology and green technology. They can empower the green transformation of the entire manufacturing chain with digital technology, drive the transformation of the green innovation paradigm with data elements, and achieve efficiency leaps. Thirdly, provinces with higher levels of digital economy can provide new tools and methods for green technology innovation through the development of digital technology, optimize enterprise production processes, improve resource utilization efficiency, and provide stronger support for the improvement of green innovation efficiency. Fourthly, resource-based provinces have long relied on resource rents, and enterprises lack the drive for green technology R&D. The digital economy may be used to strengthen traditional mining rather than innovation and upgrading. Non-resource-based provinces, due to their lack of dependence on resource dividends, are more inclined to use digital technology to optimize

clean production processes, forming a "digital-green" synergy effect, which is more conducive to improving green innovation efficiency .

### **3.2. Analysis of the Intermediary Mechanism of Digital Economy on the Efficiency of Green Innovation in Manufacturing Industry**

Based on the theory of the innovation ecosystem, the digital economy, as an exogenous technological shock, forms a multi-level transmission mechanism by reconstructing the element correlation, technological evolution, and structural network of the manufacturing innovation ecosystem . Firstly, the digital economy relies on the liquidity essence of digital elements to dissolve price distortion and information asymmetry in the traditional factor market at the micro-level. Capital, talent, and knowledge are efficiently allocated within the innovation symbiosis of "enterprise-research institution-service institution," reducing the cost of factor mismatch in green technology R&D. Secondly, digital technology builds an open innovation network relying on technology carriers such as the industrial Internet. This shifts cleaner production process improvement from linear R&D to multi-agent collaborative cooperation, inspiring the potential of green innovation efficiency through technological paradigm change. Thirdly, under the penetration of the digital economy, industrial boundaries have become blurred. Digital technology promotes the evolution of high-energy-consuming industrial clusters into a "new species" of green intelligent manufacturing. This structural upgrade reduces the marginal cost of green innovation . Based on this, this article explores the transmission effect between the digital economy and green innovation efficiency from three aspects: resource allocation efficiency, technological progress, and industrial structure upgrading.

#### **3.2.1. Optimize Resource Allocation Efficiency**

The digital economy can promote green innovation efficiency in manufacturing by improving resource allocation efficiency. According to transaction cost theory, the digital economy relies on technologies such as big data to greatly reduce the search, acquisition, processing, and verification costs of market information, significantly alleviating the problem of information asymmetry, reducing factor mismatches, and improving the liquidity and matching accuracy of various resources in the market. Simultaneously, digital technology empowers enterprises with stronger "dynamic capabilities," enabling them to identify innovation opportunities more agilely and efficiently integrate and restructure internal and external heterogeneous resources through means such as cloud computing and collaborative platforms, achieving a "new combination" of innovation elements and optimizing the structure and efficiency of resource utilization.

By leveraging digital technology, manufacturing enterprises can fully tap into idle resources, effectively reduce the scale of redundant resources within the enterprise, thereby improving the comprehensive utilization rate of resources, reducing resource usage, optimizing resource allocation, and reducing dependence on proprietary assets. With the help of digital technology, enterprises can improve their ability to identify redundant resources, integrate idle resources, resolve resource conflicts, coordinate allocation, and shift towards efficient and energy-saving production models. At the same time, enterprises can use digital technology to analyze market dynamics, understand demand, adjust internal innovation resources, reduce factor mismatch levels, accelerate the transformation of technology R&D achievements into new products and processes required by the market, increase innovation output in the achievement transformation stage, and improve achievement transformation efficiency.

#### **3.2.2. Promote Technological Progress**

Technological progress is also one of the mechanisms by which the digital economy enhances the green innovation efficiency of the manufacturing industry. That is, the digital economy can

improve its green innovation efficiency by promoting technological progress in the manufacturing industry. The technology-economy paradigm theory holds that technological progress is the engine of economic development. The digital economy presents multi-level and multi-dimensional characteristics within this theoretical framework. The transformation of technological paradigms is significantly reflected in the digital economy, shifting from the traditional industrial paradigm to a digital paradigm centered on information technology and networks. This has promoted the widespread penetration of digital technology in production, management, and transactions and has had a profound impact on the traditional economic model. In addition, the digital economy, with its convenient and flexible information flow characteristics, provides enterprises with a convenient way to acquire and absorb knowledge and information. This enables enterprises to quickly learn and accumulate new knowledge and skills, enhance their innovative knowledge base, promote technological innovation, and improve their green innovation efficiency.

The technological progress of enterprises can effectively promote the improvement of their green innovation efficiency. Technological progress drives the flow of innovative resources towards sustainable development by improving the green and low-carbon technology R&D system and catalyzes the transformation of innovation potential into industrial competitive advantages. Through the application of digital technology, technological progress improves production processes, enhances pollution treatment levels, and drives enterprises to abandon traditional production models and transform into new production models that are low-carbon, energy-saving, efficient, and have high added value.

### 3.2.3. Industrial Structure Upgrading

The digital economy stimulates the emergence of emerging industries through two paths: digital industrialization and industrial digitization, while driving the upgrading and transformation of traditional industries, thereby promoting the optimization and upgrading of the industrial structure. Digital industrialization has given rise to new services, formats, and models, while industrial digitization has promoted the improvement of production efficiency in traditional industries. The digital economy can also increase R&D personnel and capital investment, enhance market integration, and effectively promote industrial structure optimization and upgrading by optimizing resource allocation within and between regions.

Industrial structure upgrading promotes the deep transformation and upgrading of manufacturing towards high-end, intelligent, green, and integrated industries by vigorously enhancing technological innovation capabilities. Through the strategic layout of the green technology innovation ecosystem, based on the market demand traction mechanism, it collaboratively promotes breakthroughs in core low-carbon technologies, drives the efficient allocation of innovation resources to sustainable development fields, and ultimately achieves the dynamic transformation of innovation momentum into industrial comparative advantages. At the level of industrial structure evolution, relying on the dual mechanism of technological innovation capability leap and the coordinated construction of a low-carbon technology system, it systematically improves the total factor productivity of green innovation in the manufacturing industry.

## 4. Research Design

### 4.1. Measurement Model

The benchmark regression model:

$$\text{green\_efficien}_{it} = \alpha_{it} + \beta \text{digital\_economy}_{it} + \sum_{u=1}^V \gamma_u \text{Control}_{u,it} + \varepsilon_{it} \quad (1)$$

To explore the mechanism by which the digital economy affects the green innovation efficiency of the manufacturing industry, models (2) and (3) are constructed based on equation (1), as shown below:

$$M_{it} = \sigma_0 + \sigma_1 \text{digital\_economy}_{it} + \sigma_2 \text{Controls}_{it} + \mu_i + v_t + \varepsilon_{it} \tag{2}$$

$$\text{green\_efficien}_{it} = \rho_0 + \rho_1 \text{digital\_economy}_{it} + \rho_2 M_{it} + \rho_3 \text{Controls}_{i,t} + \mu_i + v_t + \varepsilon_{it} \tag{3}$$

Among them,  $M_{it}$  is the mediating variable, which includes three dimensions: resource allocation efficiency, technological progress, and industrial structure upgrading. This article examines the mediating effect of mechanism variables through the following steps: first, regression analysis is conducted on the main effect, and then model (2) is used for regression analysis. If  $\sigma_1$  is significant, model (3) is used to test the impact of the mediating variable on the green innovation efficiency of the manufacturing industry. Finally, the coefficients  $\sigma_1$  and  $\rho_1$  are compared. If both coefficients are significant, then the mediating mechanism of this article is established. Meanwhile, the proportion of indirect effects of mechanism variables is expressed as  $(\sigma_1 \times \rho_2) / (\sigma_1 \times \rho_2 + \rho_1)$ .

## 4.2. Variable Setting

The results are shown in the table below:

**Table 1.** Evaluation system of green innovation efficiency in manufacturing industry

Symbol	Primary Indicator	Secondary Indicator	Unit
Pein	Personnel input	Number of R&D personnel in the manufacturing industry	person
Enin	Energy input	Number of R&D personnel in the manufacturing industry	Billions of kilowatt-hours
Cain	Capital investment	Internal expenditure of R&D funds in the manufacturing industry	ten thousand yuan
Exou	Expected output	Sales revenue of new products in the manufacturing industry	ten thousand yuan
		Number of green patents in the manufacturing industry	document
Udou	Unexpected output	Sulfur dioxide emissions from manufacturing industry	ton
		Nitrogen oxide emissions from manufacturing industry	ton

## 5. Empirical Analysis

### 5.1. Benchmark Regression Analysis

The results are shown in the table below:

**Table 2.** Benchmark regression results of the impact of the digital economy on green innovation efficiency in the manufacturing industry

variable	Gre						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dige	0.787*** (0.227)	0.955*** (0.217)	0.739*** (0.192)	1.341*** (3.134)	0.286** (0.143)	0.484*** (0.149)	0.760*** (0.167)
Ul		-5.227 (-1.158)	-5.851 (-1.278)	-4.657 (-1.018)	-4.651 (-1.016)	-5.077 (-1.117)	-5.091 (-1.118)
Gfe			0.031 (0.825)	0.030 (0.822)	0.030 (0.816)	0.036 (0.987)	0.036 (0.977)
Evr				0.006** (2.232)	0.006** (2.212)	0.006** (2.191)	0.006** (2.185)
Fdi					5.608*** (1.452)	3.155** (1.384)	2.621* (1.789)
Led						0.671*** (0.246)	0.983*** (0.123)
Il							0.655** (0.270)
Constant	0.649*** (0.649)	0.767*** (0.064)	0.739*** (0.065)	0.686*** (0.070)	0.877*** (0.197)	0.936*** (0.201)	0.983*** (0.203)
Fixed time/region	Yes	Yes	Yes	Yes	Yes	Yes	Yes
observed value	330	330	330	330	330	330	330
R <sup>2</sup>	0.133	0.132	0.131	0.144	0.277	0.339	0.346

Note: \*, \*\*, and \*\*\* indicate significance at the 10%, 5%, and 1% levels, respectively. The robust standard errors of the estimated coefficients are in parentheses, the same applies below

### 5.2. Endogeneity Test

The results are shown in the table below:

**Table 3.** Results of endogeneity test on green innovation efficiency of manufacturing industry by digital economy

variable	Phase 1	Phase 2	Phase 1	Phase 2
	Dige	Gre	Dige	Gre
	(1)	(2)	(3)	(4)
<i>Dige</i>		0.787*** (0.222)		0.022*** (0.091)
<i>IVDige1</i>	0.721*** (0.219)			
<i>IVDige2</i>			0.569*** (0.215)	
control variable	Yes	Yes	Yes	Yes
Fixed time/region	Yes	Yes	Yes	Yes
Kleibergen-Paap rk LM statistic	10.783***		7.687***	
Cragg-Donald Wald Fstatistic	21.444		25.673	
Kleibergen-Paap Wald rk Fstatistic	28.194		11.790	
Hansen J statistical p-value	0.000		0.000	
observed value	300		300	

### 5.3. Robustness Test

The results are shown in the table below:

**Table 4.** Results of Robustness Test on Green Innovation Efficiency of Manufacturing Industry by Digital Economy

variable	Explanatory variable lags behind by one period	Replace explanatory variables	Replace the explained variable	Reduce sample size
	(1)	(2)	(3)	(4)
<i>Dige</i>	1.565*** (0.162)	0.216** (0.085)	0.867*** (0.264)	0.589* (0.317)
<i>Constant</i>	0.289*** (0.110)	0.917*** (0.203)	0.624*** (0.167)	1.165*** (0.207)
control variable	Yes	Yes	Yes	Yes
Fixed time/region	Yes	Yes	Yes	Yes
observed value	330	330	330	270
$R^2$	0.274	0.338	0.321	0.354

### 5.4. Heterogeneity Analysis

The results are shown in the table below:

**Table 5.** Heterogeneity Analysis of Green Innovation Efficiency in Manufacturing Industry by Digital Economy

variable	Regional heterogeneity			Heterogeneity of Economic Development Level		Heterogeneity of digital economy level		Heterogeneity of resource endowment	
	east	central	west	high	low	high	low	resource-based	Non resource type
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
<i>Dige</i>	0.130* (0.069)	0.538** (0.279)	0.500*** (0.168)	0.906*** (0.210)	0.445 (0.608)	0.731*** (0.191)	0.108 (0.798)	0.677 (0.141)	0.872*** (0.266)
<i>Constant</i>	0.811*** (0.215)	2.29*** (0.629)	0.737*** (0.235)	1.040*** (0.211)	0.647* (0.364)	0.963*** (0.184)	1.003*** (0.196)	0.648*** (0.336)	1.309*** (1.261)
control variable	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed time/region	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
observed value	110	66	121	165	165	165	165	143	187
$R^2$	0.546	0.613	0.167	0.481	0.163	0.551	0.197	0.215	0.280

### 6. Impact Mechanism Testing

The results are shown in the table below:

**Table 6.** Results of mediation effect test

variable	Resource allocation efficiency		technological progress		industrial structure	
	Resource allocation efficiency (1)	Green Innovation Efficiency (2)	technological progress (3)	Green Innovation Efficiency (4)	industrial structure(5)	Green Innovation Efficiency (6)
digital economy	0.169* (0.099)	0.258*** (0.062)	0.917*** (0.356)	0.866*** (0.357)	0.839*** (0.100)	0.146* (0.082)
Resource allocation efficiency		0.239* (0.133)				
technological progress				0.164* (0.099)		
industrial structure						0.156*** (0.154)
<i>Constant</i>	0.137*** (0.033)	0.652*** (0.028)	0.632*** (0.023)	0.228** (0.099)	0.612*** (0.048)	0.624*** (0.034)
control variable	Yes	Yes	Yes	Yes	Yes	Yes
Fixed time/region	Yes	Yes	Yes	Yes	Yes	Yes
observed value	330	330	330	330	330	330
$R^2$	0.258	0.243	0.329	0.316	0.542	0.280
<i>Sobel test</i>	Z=1.91*		Z=1.93*		Z=1.97*	

## 7. Conclusion and Suggestions for Countermeasures

This study empirically examines the impact of the digital economy on green innovation efficiency in China's manufacturing industry, using provincial panel data from 2012–2022. Key findings include:

The digital economy significantly enhances green innovation efficiency in manufacturing.

The effect is more pronounced in provinces with higher economic development, advanced digital economies, and non-resource-based status.

Mechanisms operate through improved resource allocation efficiency, technological progress, and industrial structure upgrading, with industrial structure upgrading being the strongest pathway.

The digital economy and manufacturing green innovation efficiency exhibit spatial agglomeration and generate a "siphon effect" spillover on neighboring regions, amplified by industrial agglomeration.

**Policy Recommendations:**

Accelerate digital economy development and guide industrial transfer. Increase digital infrastructure investment in central and western regions, encourage gradient transfer of digital industries from east to west, and promote digital cooperation between eastern enterprises and central/western regions. Tailor digital transformation strategies to regional resource endowments.

Leverage the digital economy optimally, emphasizing industrial structure upgrading. Deepen industrial transformation toward high-tech, high-value-added sectors. Integrate emerging

technologies (IoT, big data, AI, 5G) with green low-carbon industries. Provide subsidies and tax incentives and adoption of energy-saving equipment. Build high-level innovation platforms (e.g., national laboratories) and enhance industry–academia–research collaboration. Improve resource utilization efficiency via digital management systems.

Mitigate the siphon effect of digital economy highlands and promote coordinated national development. Promote balanced nationwide infrastructure layout, guiding new infrastructure (data centers, computing networks) toward less-developed regions. Establish cross-regional collaborative innovation platforms to encourage technology and talent flow. Strengthen green innovation policy guidance, integrate digital technology into low-carbon transformation of traditional industries, and leverage carbon trading and green finance mechanisms. Encourage cluster firms to pursue green, high-end, service-oriented transformation via digital technology. Foster open regional innovation networks and ensure SMEs can access and utilize digital tools for green innovation.

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