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On the U-Shaped Curve Mechanism and Heterogeneity of Digital Economy Empowering Industrial Green Development Efficiency in the Yangtze River Delta Region

Junlei Jiang*

School of Management Science and Engineering, Anhui University of Finance and Economics, Bengbu, Anhui, 233030, China

*1714897854@qq.com

Abstract

Against the dual background of global economic digital transformation and climate change response, the relationship between digital economy and industrial green development efficiency has become a research hotspot. However, existing research still lacks in-depth analysis of the relationship between the two, especially in exploring the mechanisms of action and regional differences. This study aims to clarify the impact mechanism of the digital economy on the efficiency of industrial green development in the Yangtze River Delta region through systematic analysis. Research the comprehensive use of quantitative analysis and qualitative research methods to construct a multidimensional indicator system for economic performance, digitalization level, and green transformation, in order to collect relevant data in the Yangtze River Delta region. Research has found that there is a U-shaped relationship between the efficiency of digital economy and industrial green development. In the initial stage, it was suppressed by the cost of technological substitution, but in the later stage, it achieved a leap through independent innovation. The regional heterogeneity is obvious, and the promotion effect in the Shanghai Jiangsu Zhejiang region is stronger than that in northern Anhui. This research achievement has improved the theoretical system of digital economy and green development, providing a new perspective for the interdisciplinary study of regional economics and ecological economics; At the same time, it provides scientific basis and practical guidance for the implementation of the national "dual carbon" strategy and the green transformation of enterprises, helping to promote sustainable economic and social development.

Keywords

Digital Economy; Yangtze River Delta Region; Industrial Green Development; Heterogeneity; U-shaped Curve Mechanism.

1. Introduction

Against the backdrop of actively addressing climate change and vigorously promoting sustainable development globally, industrial green development has become a key path to achieving coordinated progress between the economy and the environment (IPCC, 2021). As an important pillar of economic development, industry has long been driving economic growth, but it has also brought about problems such as excessive resource consumption and environmental pollution. Therefore, improving the efficiency of industrial green development, achieving energy conservation and emission reduction, efficient resource utilization, and ecological environment improvement are of great significance for achieving sustainable development goals.

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As one of the most developed regions in China with the most complete industrial system, the Yangtze River Delta region holds a pivotal position in the national industrial development pattern (Outline of the Yangtze River Delta Regional Integration Development Plan, 2019). However, the industrial development in the region is also facing challenges such as tightening resource constraints and increasing environmental pressure. At the same time, the digital economy is flourishing at an unprecedented speed, and new generation digital technologies such as big data, artificial intelligence, and the Internet of Things are deeply integrated with the real economy, providing new opportunities and driving forces for industrial green development (China Academy of Information and Communications Technology, 2024). The digital economy, with its characteristics of digitization, networking, and intelligence, can optimize and innovate industrial production processes, resource allocation, energy management, and other aspects, thereby enhancing the efficiency of industrial green development.

In this context, in-depth exploration of the impact of the digital economy on the efficiency of industrial green development in the Yangtze River Delta region not only helps to reveal the internal mechanism of the digital economy promoting industrial green transformation, but also provides theoretical basis and practical guidance for formulating scientific and reasonable digital economy development strategies and industrial green development policies in the Yangtze River Delta region; Moreover, it has important reference value and demonstration significance for other regions to learn from the experience of the Yangtze River Delta, promote the deep integration of digital economy and industrial green development, and achieve a win-win situation between high-quality economic development and ecological environment protection.

In today's world, the global economy is undergoing significant changes, and the wave of digitization is sweeping across various fields, becoming the core driving force for economic growth. At the same time, the issue of climate change is becoming increasingly severe, with frequent extreme weather and deteriorating ecological environment, posing huge challenges to the sustainable development of human society, prompting countries to put green and low-carbon development on their agenda. As an emerging economic form, the digital economy, with its strong innovation driving force and extensive industrial penetration, brings new opportunities for the upgrading and transformation of traditional industries, efficient utilization of resources, and optimization of production organization models. It is expected to play a key role in achieving green development goals.

As the forefront of China's economic development, the Yangtze River Delta region has abundant innovation vitality and has been a pioneer in the field of digital economy, achieving fruitful results. In 2022, the digital economy in the Yangtze River Delta will account for nearly 30% of the country's total, and significant progress will be made in digital industrialization and industrial digitization. But in the process of empowering industrial green development with digital technology, many problems are gradually emerging. At the enterprise level, in the early stages of digital transformation, there is a high cost of technological substitution, and investment in equipment updates, software purchases, and personnel training increases operational burden in the short term, which poses certain obstacles to improving green efficiency; In terms of regional development, there is a significant gap between core cities and peripheral areas. The digital economy in core cities is developing rapidly, but the digital dividends are difficult to effectively radiate to peripheral areas such as northern Anhui, exacerbating the problem of uneven development within the region; At the micro level, enterprises have multiple preferences in choosing green technologies, and the influencing factors behind them are complex and lack sufficient empirical research support. The quantitative evaluation of digital technology on enterprises' green innovation capabilities also needs to be improved.

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Based on the above background, this study focuses on the following key issues: firstly, to deeply explore the inhibitory mechanism of technology substitution costs on the efficiency of industrial green development in the early stage of digital economy development, clarify the composition of costs and their impact paths; The second is to accurately analyze the differential characteristics of the spillover effects of the digital economy in different regions of the Yangtze River Delta region, and explore the key factors that affect regional coordinated development; The third is to reveal the micro mechanism of corporate green technology preference, quantify the impact of digital technology on corporate green innovation capability, and provide scientific guidance for corporate green development [1].

This study aims to deeply analyze the intrinsic relationship between digital economy and industrial green development efficiency, and construct a more comprehensive theoretical model. Through empirical analysis, further verify and refine the nonlinear impact of digital economy on green development, especially the formation mechanism of U-shaped curve and regional heterogeneity characteristics [2]. At the same time, expanding the research boundaries of the intersection of regional economics and ecological economics, constructing a comprehensive framework that integrates multiple factors such as regional collaborative governance policies, technological innovation path selection, and energy structure optimization, provides theoretical support for understanding the multidimensional interactive relationships in complex economic ecosystems.

From a practical perspective, the research results aim to provide scientific basis and technical support for the effective implementation of the national "dual carbon" strategy. Assist the government in formulating precise and effective regional collaborative governance policies, narrowing the development gap within the Yangtze River Delta region, promoting the rational allocation of digital economic resources, and overall improving the level of green development; Provide practical guidance for the green transformation of enterprises, extract replicable successful experiences and best practice models, and promote the transformation of the industrial chain towards low-carbon direction.

This paper focuses on exploring the internal logic and practical path of digital economy driving industrial green development, and conducts in-depth research in the Yangtze River Delta region. At the theoretical level, the aim is to break through the limitations of existing research, systematically analyze the nonlinear relationship between digital economy and industrial green development efficiency, especially the formation mechanism of the U-shaped curve, and clarify the dynamic pathways of factors such as technology substitution costs and spatial spillover effects. At the same time, a comprehensive research framework covering multidimensional variables such as economic performance, digitalization level, and green transformation will be constructed, deepening the cross integration of regional economics and ecological economics, and improving the theoretical system of digital economy and green development.

In terms of practical goals, we are committed to providing scientific guidance for government decision-making and enterprise development. By revealing the differences in the level of digital economic development and the effectiveness of industrial green transformation within the Yangtze River Delta region, we aim to assist the government in formulating precise regional coordination policies, optimizing the layout of digital resources, and narrowing the regional digital divide; In response to the digital transformation and green development needs of enterprises, guide them to plan transformation paths based on their own development stages, reasonably control costs, strengthen green technology innovation, and thereby enhance market competitiveness, promote the achievement of "dual carbon" goals and sustainable industrial development.

The development of the digital economy in the Yangtze River Delta has gone through three stages: early exploration, rapid development, and deepening integration. It started with the

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application of basic digital tools, went through big data and the Internet of Things to assist energy management and pollution monitoring, and then advanced technologies to promote industrial green transformation. By 2023, the added value of the digital economy will exceed 12 trillion yuan, accounting for more than 40% of the total GDP of the three provinces and one city [3]. In theory, multiple theories such as technological innovation, industrial structure optimization, and resource allocation optimization provide support for the digital economy to drive green industrial development, covering paths such as exploring energy-saving potential, promoting low-energy consumption industries, and efficiently allocating resources [4]. In terms of research methods, previous researchers have mostly used quantitative analysis to construct econometric models, partially combining panel data and mediation effect tests, as well as qualitative case studies and multidimensional exploration methods that combine the two [5]. However, there are still shortcomings in the analysis of the complex mechanisms by which the digital economy affects the efficiency of industrial green development, the exploration of heterogeneity within the Yangtze River Delta region, as well as the timeliness of data, comprehensiveness of indicators, and integration of research methods, which urgently need to be improved and deepened.

2. Theoretical Analysis

2.1. Core Assumptions of U-shaped Relationship

The impact of the digital economy on the efficiency of industrial green development may have a "threshold effect", which is manifested as:

(1) In the initial stage. The high investment costs of the digital economy, such as technology research and development, equipment upgrades, and talent cultivation, may put pressure on the short-term profits of industrial enterprises, leading to hesitation in investing in green innovation and thus inhibiting the efficiency improvement of green development.

(2) Critical stage. When the digital economy develops to a certain level (such as improved digital infrastructure, increased technology penetration, and mature industrial digital transformation), digital technologies (such as intelligent monitoring, energy management systems, and circular economy platforms) will significantly improve resource utilization efficiency, reduce pollution emissions, and promote the efficiency improvement of green development.

2.2. The Uniqueness of the Yangtze River Delta Region

(1) Strong economic foundation. The scale of the digital economy in the Yangtze River Delta is leading in the country (such as Shanghai, Hangzhou, Nanjing and other core cities of the digital economy), but there is uneven development within the region (such as some cities in Anhui Province having relatively lagging digital levels), which may lead to regional differences in the "inflection point" of the U-shaped curve.

(2) The industrial structure is complex. Traditional manufacturing industries (such as steel and chemicals) coexist with high-tech industries. The digital transformation of traditional industries is difficult and may have a negative impact on green efficiency in the early stages, while emerging industries are more likely to benefit from digital technology.

3. Research Design

This study is based on systems analysis theory, constructing a multidimensional research framework with the level of digital economy development as the independent variable, industrial green development efficiency as the dependent variable, technology substitution cost and spatial spillover effects as mediating variables, and regional characteristics, industrial structure, etc. as control variables [6]. Through the theories of neoclassical economics and environmental economics, this paper deeply analyzes the role of the digital economy in

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promoting green industrial development, such as reducing energy consumption through technological innovation and optimizing resource allocation through industrial digitization [7]. By combining theoretical analysis with empirical testing, using econometric and spatial econometric models, the direct and indirect effects between variables are verified, revealing regional heterogeneity and spatial spillover patterns[8].

Table 1. Variable Setting

Variable type	Variable	Example of proxy indicators
Core explanatory variables	Development level of digital economy	Digital infrastructure index, proportion of digital industry output value, Internet penetration rate
Explained Variable	Industrial green development efficiency	Total factor energy productivity, carbon emission intensity per unit of GDP, industrial wastewater recycling rate
control variable	Economic development level, industrial structure, environmental regulation intensity, research and development investment, etc	GDP growth rate, proportion of high-tech industries, number of environmental policies, and R&D investment

The sample is selected from 27 cities in the Yangtze River Delta region, covering the period from 2016 to 2023 (or the latest available year). Construct an indicator system from three dimensions: economic performance, digitalization level, and green transformation, covering multiple indicators such as per capita GDP, carbon emission intensity per unit GDP, broadband penetration rate, and industrial wastewater treatment rate, to ensure regional representativeness and data standardization. The data mainly comes from official websites such as the National Bureau of Statistics, the Ministry of Industry and Information Technology, and the Ministry of Ecology and Environment, as well as statistical yearbooks of various provinces and cities. Interpolation and mean methods are used to fill in missing values, and standardized to eliminate dimensions. In empirical analysis, descriptive statistics and correlation analysis are first conducted, followed by the construction of panel data models, mediation effect models, and spatial Durbin models to test variable relationships [9]. Robustness tests are conducted by replacing indicators, changing sample intervals, and other methods to ensure the reliability of research results.

4. Empirical Results and Analysis

When the level of development of the digital economy is below the critical value, its impact coefficient on industrial green efficiency is negative ($\beta<0$), showing a inhibitory effect; When the level of development of the digital economy exceeds the critical value, the impact coefficient becomes positive ($\beta>0$), showing a promoting effect. Mathematical expression:

$$Green\ efficiency\ i=\alpha+\beta_1\ digital\ economy\ i+\beta_2\ digital\ economy\ i_2+\gamma\ control\ variable\ i+\varepsilon_i$$

Among them, $\beta_2>0$ indicates the existence of a U-shaped relationship.

Developed cities with digital economy such as Shanghai and Hangzhou have crossed the inflection point of the U-shaped curve, and the promotion of green efficiency by the digital economy is significant. Some prefecture level cities in Anhui and Jiangsu are still on the left side of the U-shaped curve, and digital economy investment has not yet been fully transformed into green efficiency improvement.

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Descriptive statistics on sample data in the Yangtze River Delta region show significant differences in economic performance, digitalization level, and green transformation among cities within the region. Core cities such as Shanghai, Nanjing, and Hangzhou have high per capita GDP and labor productivity, outstanding digital indicators such as broadband penetration rate, and significant green transformation effects such as industrial wastewater treatment rate. However, some cities in northern Anhui have low economic performance, lagging digital construction, and slow green transformation process. At the same time, the radiation and driving effect of the digital economy in core cities on the surrounding areas decreases with distance, and the radiation in northern Anhui is relatively weak.

Regression analysis confirms a U-shaped relationship between the efficiency of digital economy and industrial green development. In the early stages of the development of the digital economy, the high cost of technology substitution such as equipment procurement and software research and development hindered the efficiency of industrial green development; With the development of the digital economy, the innovation capability of enterprises has been enhanced, and technological bottlenecks have been overcome through methods such as green patent conversion, achieving a leap in green efficiency. Regional heterogeneity analysis shows that the promotion effect of digital economy on industrial green development efficiency in the Shanghai Jiangsu Zhejiang region is significantly stronger than that in the northern Anhui region. In addition, the mechanism of the role of factors such as technology substitution cost and spatial spillover effect was further verified through data statistical analysis, and the research results were visually presented using relationship graphs, bar charts, and other charts.

5. Conclusion and Suggestions

This study, through empirical analysis of the Yangtze River Delta region, clarifies that there is a U-shaped relationship between the efficiency of digital economy and industrial green development, with technology substitution costs playing a partial mediating role and significant regional heterogeneity. The promotion effect of digital economy on industrial green development in the Shanghai Jiangsu Zhejiang region is stronger than that in the northern Anhui region, and the spatial spillover effect also varies depending on the region. In theory, the mechanism model of the interaction between digital economy and green development has been improved, and the research on the intersection of regional economics and ecological economics has been expanded; In practice, it provides scientific basis and guidance for the implementation of the national "dual carbon" strategy, precise policy formulation by the government, and green transformation of enterprises, helping to promote regional coordinated development and green upgrading of enterprises.

The impact of the digital economy on industrial green efficiency in the Yangtze River Delta exhibits a U-shaped nonlinear relationship, with significant regional heterogeneity. Targeted policies need to be formulated to promote low digital cities to cross the "critical turning point".

For cities located on the left side of the U-shape (such as some areas in Anhui): increase investment in digital infrastructure, reduce the cost of digital transformation for enterprises, and prioritize the promotion of energy-saving digital technologies (such as smart grids and carbon management systems) in high energy consuming industries.

For cities located on the right side of the U-shape (such as Shanghai and Hangzhou): deepen the integration of digital technology and green industries, develop digital finance to support green innovation, and establish a regional collaborative green digital ecosystem [10].

This study has distinctive features in sample selection, research methods, and result analysis, which are of great significance for policy formulation and corporate practice. At the policy level, the government should increase investment in digital infrastructure construction in northern Anhui and other regions to narrow the regional digital divide; Introduce policies to encourage

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green technology innovation in enterprises and reduce the cost of technological substitution; Strengthen regional coordinated development planning and promote resource sharing. At the enterprise level, it is necessary to plan digital transformation and green development paths reasonably according to its own development stage, focusing on cost control in the early stage and increasing innovation investment in the later stage to enhance green competitiveness.

There are certain limitations to the research, as the scope is limited to the Yangtze River Delta region and does not involve comparisons with other regions; Insufficient consideration of the impact of changes in the international digital economy environment; In terms of indicator selection, some indicators are difficult to fully and accurately reflect the true situation of the research object. Future research can expand nationwide and even globally, comparing the development patterns of different regions; Deeply explore the impact mechanism of changes in the international digital economy environment on the green development of domestic industries; Further optimize the indicator system, incorporate more relevant factors such as emerging technologies and markets, and more accurately measure the impact of the digital economy on the efficiency of industrial green development.

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