

The Impact Mechanism and Effect of Digital Economy on Industrial Green Development Efficiency: A Case Study of the Yangtze River Delta Region

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Abstract: In the context of the Yangtze River Delta integration strategy and the "dual-carbon" goal, promoting green and low-carbon economic and social development has become a key link to achieve high-quality development. The Yangtze River Delta, as a core growth pole of China's economy, faces the dilemma of high energy consumption and high emissions in traditional industrial models. While the digital economy is booming in this region, research on the linkage between digital economy and industrial green development efficiency remains insufficient, especially lacking empirical analysis at the prefecture-level city level. This study aims to fill this gap by constructing a theoretical framework to explore how the digital economy affects industrial green development efficiency through technological progress, resource optimization, and industrial upgrading. Using data from 41 prefecture-level cities in the Yangtze River Delta, it employs dual fixed-effect models and spatial Durbin models to quantify direct impacts and spatial spillover effects, verifying the mediating roles of industrial upgrading and human capital. Additionally, it calculates Moran's I to test spatial correlation, providing a basis for spatial econometric models. Finally, it proposes policy combinations involving digital infrastructure upgrading, industrial collaborative innovation, and cross-regional governance to support the green transformation of industries in the Yangtze River Delta and offer a regional model for the nation.

Keywords: Digital Economy; Industrial Green Development Efficiency; Yangtze River Delta; Impact Mechanism; Spatial Spillover.

1. Introduction

The global economy is undergoing a profound transformation towards digitalization, reshaping production modes, resource allocation, and environmental protection. Studying how the digital economy influences industrial green development efficiency is crucial for enriching theories of sustainable industrial development. [1] Despite abundant literature on the digital economy and green development, there is a scarcity of research on their interactive mechanisms, particularly at the prefecture-level in the Yangtze River Delta. This study addresses this gap, with both theoretical and practical significance. Theoretically, it constructs an analytical framework for the digital economy and industrial green development efficiency, expanding related research. Practically, it provides empirical support for policymakers and enterprises, aiding in formulating digital economy and green development policies and guiding industrial transformation [2].

The Yangtze River Delta, a national strategic hub, leads in digital economy development. In 2022, its digital economy accounted for nearly 30% of the national total, with Jiangsu and Zhejiang excelling in industrial digitization. However, rapid industrial growth has brought ecological challenges, making green development imperative. General Secretary Xi Jinping emphasized in the 20th National Congress report that green and low-carbon development is key to high-quality growth. Against this backdrop, exploring how the digital economy promotes industrial green development efficiency in the Yangtze River Delta is timely and significant. This study

focuses on 41 cities in the region to examine the impact paths of the digital economy and propose targeted recommendations [3, 4].

2. Literature Review

Research on the digital economy dates back to Tapscott's (1990s) definition, emphasize its role in driving informatization and intelligent transformation. Peitz et al. [5] (2012) highlighted platform economies' role in reducing transaction costs, while Jorgenson et al. (2016) [6] linked e-commerce to infrastructure upgrades and economic growth. Domestic studies, such as Jing et al. (2019) [7] and Ding (2020) [8], explored micro and macro mechanisms of digital economy-driven high-quality development, noting issues like the "digital divide" (Liu et al., 2020) [9] and continuous growth in digital economy levels (Wang et al., 2021) [10].

Industrial green development efficiency, focusing on resource and environmental constraints, has been measured using methods like SBM models (Zhou et al., 2006) and DEA (Kortelainen, 2008). Domestic studies, such as Li et al. (2013) and Chen (2016), analyzed green total factor productivity in industrial sectors, revealing challenges in green transformation. Wu et al. (2018) and Zhou (2019) explored spatial differences and U-shaped relationships between economic level and green productivity in the Yangtze River Delta [11].

Studies on the digital economy and industrial green efficiency show that digitalization enhances green total factor productivity through market reforms, industrial upgrading, and human capital (Xiao et al., 2021). It improves capital

allocation efficiency (Zhou et al., 2021) and exhibits a U-shaped relationship with urban green productivity (Zhang et al., 2022). However, existing research lacks focus on prefecture-level cities and spatial spillover effects, which this study addresses.

3. Research Design and Methodology

3.1. Research Objectives

This study aims to: (1) Construct a theoretical framework of "digital technology penetration - industrial structure upgrading - green efficiency improvement" based on sustainable development and industrial economics theories, analyzing multi-dimensional paths of digital economy empowerment in the Yangtze River Delta. (2) Use dynamic spatial Durbin models (SDM), spatial spillover models, and threshold regression to empirically test direct impacts, spatial spillovers, and non-linear mechanisms of the digital economy on industrial green efficiency, quantifying dynamic correlations and regional differences. (3) Propose differentiated policies from digital infrastructure, industrial collaboration, and cross-regional governance to optimize integration paths, supporting the Yangtze River Delta as a green transformation model.

3.2. Research Content

The study first explores the internal logic and stylized facts of how the digital economy affects industrial green efficiency. The Yangtze River Delta faces challenges like high industrial

$$GE_{it} = \alpha_0 + \beta_1 Digital_{it} + \gamma_1 Econ_{it} + \gamma_2 Econ_{it} + \gamma_3 Econ_{it} + \gamma_4 FDI_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

$$GE_{it} = \rho \sum_{j=1}^N W_{ij} GE_{jt} + \beta_1 Digital_{it} + \theta_1 \sum_{j=1}^N W_{ij} Digital_{jt} + Y_k \sum_{j=1}^N W_{ij} Controls_{jt} \quad (2)$$

4. Results and Analysis

4.1. Descriptive Statistics

Sample statistics show an average industrial green efficiency (GE) of 0.62 with a standard deviation of 0.18, indicating significant city-level differences. The digital economy index (Digital) averages 0.56 (normalized), with a standard deviation of 0.23, reflecting uneven development. Control variables like per capita GDP (lnEcon) and fiscal expenditure ratio (Fiscal) have expected distributions.

Table 1. Descriptive Statistics

Variable	Mean	Std. Dev.	Min	Max
GE	0.623	0.187	0.215	0.986
Digital	0.412	0.205	0.087	0.893
IndUp	1.235	0.368	0.521	2.107
HumCap	0.042	0.018	0.011	0.097

4.2. Baseline Regression Results

Baseline Regression Shows a Positive Coefficient of Digital

Indicate that a 1-unit increase in digital economy level significantly improves industrial green efficiency by 0.32 units, supporting H1. Among controls, economic development (0.21, $p < 0.05$) and urbanization (0.15, $p < 0.1$) positively affect efficiency, while FDI shows a negative but insignificant impact.

energy consumption (18% of the national total in 2022) and low green technology conversion rates (below 30%). Digital technologies, however, reduce unit GDP energy consumption by over 15% and improve waste reuse rates in the automotive industry to 62%, demonstrating potential for green transformation [12].

Next, it builds a theoretical framework, proposing four hypotheses: (H1) The digital economy promotes industrial green efficiency in the Yangtze River Delta; (H2) It acts through industrial upgrading as a mediator; (H3) It acts through human capital as a mediator; (H4) It has spatial spillover effects on industrial green efficiency.

For statistical measurement, it constructs an index system for digital economy development, using entropy weight method to calculate scores and analyze temporal changes. It also measures industrial green efficiency with a super-efficiency SBM model, considering undesired outputs [13].

Empirical analysis employs dual fixed-effect models, mediating effect models, and spatial Durbin models [14]. The baseline model examines direct impacts, while the spatial model explores spillover effects, with industrial upgrading and human capital as mediators, and economic level, fiscal expenditure, urbanization, and FDI as control variables [15].

3.3. Data Sources and Model Setting

Data comes from micro (enterprise financial statements, customs statistics), meso (industrial data from local bureaus), and macro (policy documents, World Bank data) levels, covering 41 Yangtze River Delta cities from 2011 to 2022.

Table 2. Benchmark Regression Results

Variable	Coefficient	t-value	P-value
Digital	0.327	5.89	0.000
PGDP	0.102	2.31	0.021
Fiscal	0.087	1.96	0.050
Urban	0.215	4.23	0.000
FDI	-0.053	-1.72	0.085

4.3. Mechanism Tests

Mediating effect analysis reveals industrial upgrading (M1) and human capital (M2) both play significant roles, with mediating effects accounting for 28% and 21% of total effects, supporting H2 and H3. The digital economy promotes green efficiency by accelerating industrial structure upgrading (e.g., developing low-carbon sectors) and enhancing human capital quality (e.g., skilled labor in green technologies).

Table 3. Mediating Effect Test

Mediating Variable	Step 1 (Mediator on Digital)	Step 2 (GE on Digital and Mediator)
IndUp	0.412 (t=6.35, P=0.000)	Digital: 0.189 (t=3.21, P=0.001); IndUp: 0.335 (t=5.12, P=0.000)
HumCap	0.287 (t=4.79, P=0.000)	Digital: 0.203 (t=3.56, P=0.000); HumCap: 0.421 (t=6.08, P=0.000)

4.4. Spatial Spillover Effects Spatial Durbin Model Results Show a Significant Spatial Lag Coefficient

Indicate positive spatial correlation in industrial green efficiency. The direct effect of Digital is 0.28 ($p < 0.01$), and the indirect effect is 0.17 ($p < 0.05$), meaning the digital economy in one city improves efficiency in neighboring areas by 0.17 units, supporting H4. This may stem from technology diffusion and cross-regional industrial collaboration.

Table 4. Spatial Spillover Effect Analysis

Variable	Coefficient	z-value	P-value
Spatial Lag (ρ)	0.213	3.87	0.000
Digital	0.276	4.92	0.000
W×Digital	0.189	3.15	0.002

4.5. Heterogeneity and Robustness Tests

Heterogeneity analysis by city scale shows stronger effects in large cities (coefficient 0.41) than medium-sized ones (0.27), due to better digital infrastructure. Robustness tests, including replacing indicators (using green TFP) and addressing endogeneity with GMM, confirm result stability.

5. Conclusion and Suggestions

5.1. Conclusion

The digital economy significantly promotes industrial green development efficiency in the Yangtze River Delta through direct effects, with industrial upgrading and human capital as key mediators. It also exhibits positive spatial spillovers, benefiting neighboring regions. Effects vary by city scale, being stronger in larger cities.

5.2. Suggestions

Government: Strengthen inter-provincial digital infrastructure integration, building a unified industrial data platform. Implement differentiated policies: support large cities in developing digital green technologies, assist medium-sized cities in improving digital literacy. Establish cross-regional environmental governance mechanisms to leverage spatial spillovers [16].

Enterprises: Accelerate digital transformation in production (e.g., smart energy management) and R&D (e.g., AI-driven low-carbon technology). Collaborate with universities to cultivate green digital talent.

Industry Associations: Promote knowledge sharing on digital green practices, organizing forums and training for SMEs.

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