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Green finance–digital supply chain synergy and international logistics trade efficiency: evidence from China's Jing-Jin-Ji urban agglomeration

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Abstract. This paper examines the impact of green finance–digital supply chain synergy on international logistics trade efficiency in the Jing-Jin-Ji region and explores the underlying mechanisms. Using panel data for 13 cities from 2013 to 2024, this study constructs green finance and digital supply chain indices based on the entropy weight method and measures their synergy using a coupling coordination degree model. International logistics trade efficiency is estimated through a super-efficiency DEA model, and a fixed-effects model is employed for empirical analysis. The results show that green finance, digital supply chains and their synergistic development exhibit an overall upward trend despite regional disparities. Green finance–digital supply chain synergy significantly improves international logistics trade efficiency, with stronger effects observed in regions with higher levels of development. Further analysis reveals that resource allocation efficiency and digital financial inclusion serve as important transmission channels. These findings provide new evidence on the role of financial and digital synergies in enhancing logistics performance and offer policy implications for promoting coordinated regional development and high-quality trade growth.

Keywords: green finance, digital supply chains, international logistics trade efficiency, green finance–digital supply chain synergy, Jing-Jin-Ji urban agglomeration

1. Introduction

The transition toward green and digital development has become a key priority for achieving high-quality economic growth in China. In particular, the *Report to the 20th National Congress of the Communist Party of China* emphasized the need to accelerate the green transformation of development patterns and deepen the integration of the digital economy with the real economy. Against this backdrop, green finance and digital supply chains have emerged as important engines of regional economic transformation. Green finance promotes sustainable development by optimizing resource allocation and supporting green innovation, while digital supply chains improve operational efficiency and coordination through the application of digital technologies such as big data, artificial intelligence and the Internet of Things. Their interaction creates synergistic effects that contribute to the modernization of industrial and supply chain systems.

As a critical bridge connecting domestic and international markets, international logistics plays a fundamental role in facilitating trade flows and enhancing regional openness. Improving international logistics trade efficiency is therefore essential for promoting high-quality economic development and strengthening China's dual-circulation development pattern. As one of China's most important urban agglomerations, the Jing-Jin-Ji region serves as a strategic platform for coordinated regional development and high-level opening-up. Investigating how the synergistic development of green finance and digital supply chains affects international logistics trade efficiency in this region is thus of considerable theoretical significance and practical relevance.

Current research on green finance, digital supply chains, and international logistics trade efficiency has attracted increasing attention. Kai Lin et al. [1] propose that green finance promotes high-quality economic development and generates significant spatial spillover effects through resource allocation and technological innovation. Yuhao Li et al. [2] argue that green finance contributes to export quality improvement by facilitating digital transformation and green development. International evidence provided by Jun Zhu and Jiazhuo Xie [3], Mohamed Djafar Henni et al. [4], and Junwen Luo et al. [5] further confirms the positive roles of green finance in urban green development, corporate resilience, and energy transition. In addition, Jian Huang et al. [6] find that green supply chain finance alleviates financing constraints and improves supply chain stability, while Shoulin Liu and Wei Wei [7] emphasize its contribution to industrial chain resilience. Ling Dai et al. [8] point out that the integration of green finance and logistics industries accelerates green industrial transformation. Meanwhile, digital supply chains have become an important direction for supply chain modernization. Yunqiu Nie et al. [9] propose that digital infrastructure, intelligent technologies, and supply chain operations constitute the foundation of digital supply chain development. Hua Song [10]and Chaoyi Xu et al. [11] argue that digital technologies improve supply chain coordination, reduce logistics costs, and enhance industrial competitiveness. Le Tho V. and Ruoling Fan [12] point out that digital twin technologies strengthen real-time monitoring and intelligent decision-making capabilities within logistics systems. However, Kai Liang [13] notes that considerable regional disparities still exist in the development of digital industries and logistics sectors in the Beijing–Tianjin–Hebei region.International logistics trade efficiency is widely regarded as an important indicator of regional openness and trade competitiveness. Zhizhai Zhang et al. [14] argue that trade barriers increase logistics costs and reduce logistics efficiency, whereas improvements in logistics infrastructure and trade facilitation contribute to a better logistics environment. Ting Ding et al. [15] further confirm that enhanced cross-border logistics performance significantly improves export competitiveness. Moreover, Jiahui Yi et al. [16] find that green finance affects economic performance through resource allocation optimization and supply chain spillover effects, providing a new perspective for understanding the interaction between finance and logistics systems. Overall, existing studies have extensively examined green finance, digital supply chains, and international logistics trade efficiency from separate perspectives. However, limited attention has been paid to the synergistic effects between green finance and digital supply chains. In particular, evidence regarding how their coordinated development affects international logistics trade efficiency under the background of regional integration, especially in the Beijing–Tianjin–Hebei region, remains insufficient. Therefore, this study investigates the impact and transmission mechanisms of green finance–digital supply chain synergy on international logistics trade efficiency, with the aim of providing new empirical evidence for promoting coordinated regional development and high-quality trade growth.

Against this backdrop, the Jing–Jin–Ji region provides an ideal setting to examine the interaction between green finance and digital supply chains. As China's first national strategy for coordinated regional development, it has played an important role in promoting both green transformation and digital economic

development. According to the *Beijing–Tianjin–Hebei Logistics Coordinated Development Report (2014–2023)*, the regional logistics industry reached RMB 564.35 billion in value added in 2023, with freight volume of 344.9 million tons, reflecting continued improvements in logistics capacity and regional connectivity (Data source: https://www.gov.cn/lianbo/difang/202409/content_6974442.htm?). At the same time, the diffusion of digital technologies such as big data, artificial intelligence, and the Internet of Things, together with the development of green finance, has created favorable conditions for the digital and sustainable upgrading of supply chains. To address gaps in the existing literature, this study uses panel data from 13 cities in the Jing–Jin–Ji region over 2013–2024 to examine the impact of green finance–digital supply chain synergy on international logistics trade efficiency. It further investigates the underlying mechanisms and heterogeneity of this relationship. By integrating financial and digital dimensions into a unified framework, the study provides new evidence on the drivers of logistics efficiency from a regional integration perspective and offers policy implications for high-quality trade development.

2. Theoretical framework and research hypotheses

Green finance and digital supply chains are two key drivers of green and digital transformation. Green finance supports sustainable development by directing capital toward environmentally friendly projects and promoting technological innovation, while digital supply chains improve operational efficiency and coordination through technologies such as big data, artificial intelligence, and the Internet of Things. Rather than operating independently, the two increasingly exhibit complementarities in the process of industrial upgrading.

Their integration promotes the green and intelligent transformation of logistics systems through multiple channels. Green finance alleviates financing constraints and provides capital support for digital technology adoption and logistics infrastructure upgrading. In turn, digital supply chains enhance information transparency, reduce transaction costs, and improve resource coordination, thereby increasing capital allocation efficiency and facilitating green investment implementation. Through the mutual reinforcement of financial support and digital empowerment, their synergy contributes to more efficient and resilient logistics networks and supports improvements in international logistics trade efficiency.

2.1. The interaction between green finance and digital supply chains

2.1.1. The enabling role of green finance

Green finance facilitates the development of digital supply chains through financial support, market incentives, and policy guidance. By alleviating financing constraints, instruments such as green credit and green bonds provide essential funding for digital infrastructure, smart logistics, and supply chain upgrading. In addition, the expansion of green investment and digital inclusive finance promotes the adoption of advanced technologies and accelerates the digital and intelligent transformation of supply chain systems, thereby improving overall efficiency and resilience.

2.1.2. The reinforcing effect of digital supply chains

Conversely, digital supply chains enhance the effectiveness of green finance by improving information transparency and resource allocation efficiency. The diffusion of digital technologies and data-sharing platforms reduces information asymmetry and lowers the transaction costs of green financing. Moreover, technologies such as big data and artificial intelligence improve the identification, evaluation, and monitoring of green projects, thereby increasing the efficiency and accuracy of green credit and investment decisions. As a result, digital supply chains provide both technological support and application scenarios for green finance, generating a mutually reinforcing relationship and stronger synergistic effects.

2.2. Green finance–digital supply chain synergy and international logistics trade efficiency

The synergistic development of green finance and digital supply chains contributes to international logistics trade efficiency through the combined effects of financial support and digital empowerment. Green finance facilitates the upgrading of logistics infrastructure and promotes green technological innovation, while digital supply chains improve operational efficiency by enhancing information sharing, optimizing resource coordination and enabling intelligent decision-making. As financial resources become increasingly integrated with digital technologies, the interaction between the two generates cumulative benefits that strengthen the efficiency and resilience of logistics networks. Consequently, their synergistic development is expected to improve international logistics trade efficiency.

Accordingly, the following hypothesis is proposed:

H1. Green finance–digital supply chain synergy positively affects international logistics trade efficiency.

2.3. The mediating role of resource allocation efficiency

In addition to its direct effect, the synergy between green finance and digital supply chains may enhance international logistics trade efficiency by improving resource allocation efficiency. Green finance guides capital toward environmentally friendly and high-productivity sectors, while digital supply chains increase the efficiency of factor matching through information sharing and intelligent decision-making. These processes help reduce resource misallocation and improve the allocation of capital, technology and labor across economic activities. As resource allocation becomes more efficient, logistics enterprises are better positioned to optimize production processes and enhance trade performance.

Accordingly, the following hypothesis is proposed:

H2. Resource allocation efficiency mediates the relationship between green finance–digital supply chain synergy and international logistics trade efficiency.

2.4. The mediating role of digital inclusive finance

The synergistic development of green finance and digital supply chains may also affect international logistics trade efficiency through digital inclusive finance. The expansion of digital supply chains creates diversified application scenarios for digital financial services, while the development of green finance encourages financial innovation and broadens access to financial resources. Their interaction promotes the coverage and accessibility of digital financial services, alleviates financing constraints and improves the efficiency of financial resource allocation. As a result, enterprises engaged in international logistics and trade are able to obtain more flexible and efficient financing support, thereby enhancing their operational performance and competitiveness.

Accordingly, the following hypothesis is proposed:

H3. Digital inclusive finance mediates the relationship between green finance–digital supply chain synergy and international logistics trade efficiency. The theoretical framework underlying these relationships is presented in Figure 1.

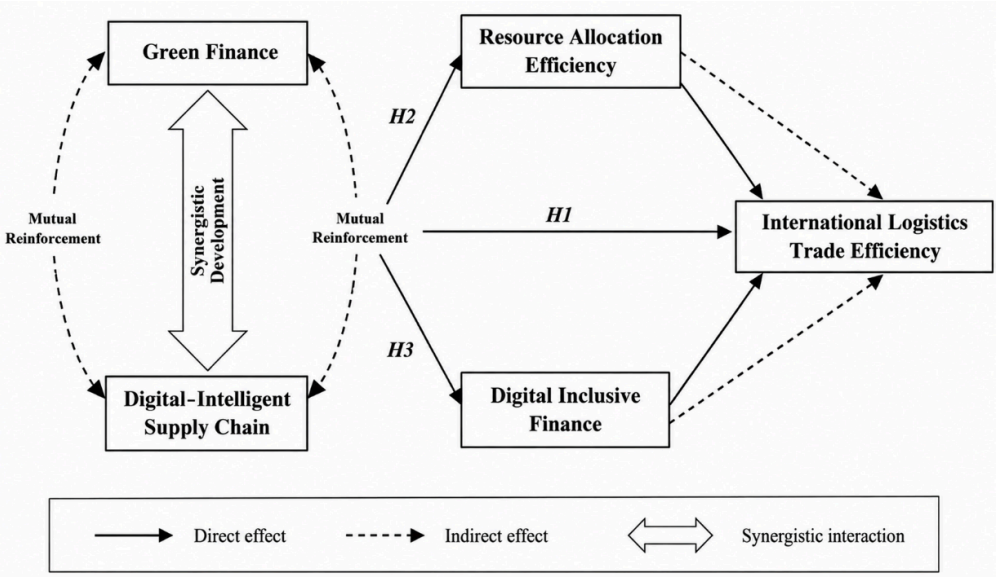

Figure 1. Theoretical framework of the relationship between green finance–digital supply chain synergy and international logistics trade efficiency

3. Methodology

3.1. Dependent variable: international logistics trade efficiency

International Logistics Trade Efficiency (ILTE) is an important indicator of a region's capacity to allocate logistics resources and support international trade activities. Given the multidimensional nature of logistics systems, this study employs Data Envelopment Analysis (DEA) to measure efficiency in the Jing–Jin–Ji region.

Table 1. Indicator system for evaluating international logistics trade efficiency

Indicator Type	name of index	Indicator Description	unit
Input Indicator	human input	Number of employees in the transportation, storage, and postal industries	thousands of people
	capital input	gross fixed asset formation	Wan Yuan
	Infrastructure Investment	highway mileage	kilometre
Output Indicator	Trade Output	Total import and export value of the region	Wan Yuan
	Logistics Output	Total Freight Volume	tonnes

To improve the discriminatory power of efficiency estimates, an input-oriented super-efficiency CCR DEA model is applied. The analysis is based on a panel dataset of 13 cities from 2013 to 2024, with each city-year observation treated as a Decision-Making Unit (DMU). Following the existing literature, the evaluation system includes three input categories—labor, capital, and infrastructure investment—and two output indicators, namely trade output and logistics output, capturing regional trade performance and logistics service capacity. The detailed indicator system is presented in Table 1.

3.2. Core explanatory variable: green finance–digital supply chain synergy

The synergistic development of green finance and digital supply chains serves as the core explanatory variable in this study. The interaction between the two systems plays an important role in promoting the green and digital transformation of the logistics industry. Green finance provides financial support for sustainable projects and supply chain upgrading, while digital supply chains enhance resource allocation and operational efficiency through digital technologies. Their interaction generates complementary effects that improve the efficiency of logistics and trade activities.

Following Li et al. [17], the Green Finance subsystem (GF) is constructed from three dimensions: resource supply, market regulation, and policy support, including indicators such as green credit, green bonds, green funds, and fiscal environmental expenditure. In parallel, based on Nie et al. [9], the Digital Supply Chain subsystem (DSC) is developed from three dimensions: digital infrastructure, intelligent empowerment, and operational performance, including indicators such as internet penetration, e-commerce development, AI-related indicators, and logistics efficiency measures.

To measure the interaction between the two systems, the entropy weight method is first used to construct composite indices for GF and DSC, followed by the coupling coordination degree model to calculate their level of synergy, denoted as D. The detailed indicator systems are presented in Tables 2 and 3.

Table 2. Evaluation indicator system for Green Finance (GF) development

Primary Indicator	Secondary Indicator	Indicator Description	unit	attribute	weight
Resource Supply Side	green-credit policy	Total amount of credit for environmental protection projects / Total loan amount	%	the first month of the lunar year	0.106
	Green Bond	Green bond issuance amount / Total bond issuance amount	%	the first month of the lunar year	0.319
	Green Fund	Green Fund Size / Total Fund Size	%	the first month of the lunar year	0.132
Market Regulation Layer	Green Insurance	Environmental Pollution Liability Insurance Revenue / Total Premium Revenue	%	the first month of the lunar year	0.147
	Green Rights Market	Carbon Trading Volume / Equity Market Trading Volume	%	the first month of the lunar year	0.110
Policy Guidance Layer	Green Investment	Investment in Environmental Pollution Control / Regional GDP	%	the first month of the lunar year	0.082
	Green Financial Support	Environmental protection expenditure / Total fiscal expenditure	%	the first month of the lunar year	0.104

Table 3. Evaluation indicator system for the development of digital and intelligent supply chain (DSC)

Primary Indicator	Secondary Indicator	Indicator Description	unit	attribute	weight
Digital Foundation	Internet penetration rate	Number of internet users per 100 people / Resident population	Household/Person	the first month of the lunar year	0.058
Digital Foundation	Level of development of the e-commerce industry	E-commerce Sales Amount / area GDP	%	the first month of the lunar year	0.126
Intelligent Empowerment	Artificial Intelligence Enterprise Density	Number of AI Companies / Total Number of Companies	%	the first month of the lunar year	0.210
	artificial intelligence Level of innovation output	Number of Artificial Intelligence Patents / Permanent population	Per 10,000 people	the first month of the lunar year	0.398
	Software Industry Strength	Number of employees in the information services industry / Total number of employed individuals	%	the first month of the lunar year	0.035
Supply chain operational efficiency	Logistics Output Efficiency	Postal Service Volume per Resident Population	Yuan per person	the first month of the lunar year	0.114
	Logistics employment intensity	Logistics Industry Employees / Total number of employed individuals	%	the first month of the lunar year	0.028
	Level of development in circulation systems	Total retail sales of consumer goods / Regional GDP	%	the first month of the lunar year	0.031

Note: The weights for both systems are calculated using the entropy weight method.

To quantify the degree of interaction between green finance and digital supply chains, this study first applies the entropy weight method to construct the composite indices of Green Finance (GF) and Digital Supply Chains (DSC). Compared with subjective weighting approaches, the entropy weight method determines indicator weights according to the amount of information contained in each indicator and thus provides a more objective assessment of subsystem development.

The entropy weight of each indicator is calculated as Equations (1)-(5):

$$w_j = \frac{1-e_j}{\sum_{j=1}^{m}(1-e_j)} \tag{1}$$

where: e_j denotes the entropy value of indicator, and w_j represents the corresponding weight.

The composite index for each subsystem is then obtained by Equation (2):

$$U_i = \sum_{j=1}^{m} w_j x_{ij} \tag{2}$$

where: x_{ij} is the standardized value of indicator, and U_i represents the comprehensive evaluation index. Hereafter, GF denotes the Green Finance Composite Index, while DSC represents the Digital and Intelligent Supply Chain Composite Index.

Based on the two composite indices, the coupling coordination degree model is employed to evaluate their synergistic development. The coupling degree is calculated as Equation (3):

$$C = \frac{2\sqrt{GF \times DSC}}{GF + DSC} \tag{3}$$

where: C denotes the coupling degree between the two subsystems.

The comprehensive development index is defined as Equation (4):

$$T = \alpha GF + \beta DSC \tag{4}$$

where: T reflects the overall development level of the two systems. Following previous studies, equal importance is assigned to the two subsystems, with $\alpha = \beta = 0.5$.

Finally, the degree of synergistic development is measured by the coupling coordination index Equation (5):

$$D = \sqrt{C \times T} \tag{5}$$

where: D denotes the level of green finance–digital supply chain synergy. A higher value of D indicates stronger coordination and a greater degree of synergistic development between the two subsystems.

3.3. Mediating variables

3.3.1. Resource allocation efficiency

Resource Allocation Efficiency (RAE) reflects the efficiency with which production factors are utilized and is an important determinant of high-quality economic development. The synergistic development of green finance and digital supply chains is expected to improve the allocation of capital, labor, and technology, thereby enhancing overall resource utilization efficiency. Following the existing literature, RAE is proxied by labor productivity, measured as the ratio of regional GDP to total employment. A higher value indicates more efficient allocation of production factors within the regional economy.

3.3.2. Digital inclusive finance

Digital Inclusive Finance (DIF) refers to the integration of digital technologies with financial services and plays an increasingly important role in improving financial accessibility and resource allocation efficiency. The synergy between green finance and digital supply chains can alleviate financing constraints and improve access to credit, particularly for small and medium-sized enterprises. In turn, digital inclusive finance supports cost reduction, improved financial inclusion, and more efficient resource allocation, thereby facilitating logistics and trade development. Accordingly, DIF is included as a mediating variable and is measured using the Peking University Digital Financial Inclusion Index.

3.4. Control variables

To account for other determinants of international logistics trade efficiency, this study includes a set of commonly used regional control variables. Specifically, Per capita GDP (PGDP), Industrial Structure Sophistication (ISU), Urbanization Level (UL), Cross-border Logistics Support capacity (CLS), and R&D Investment intensity (RDI) are incorporated into the regression model. Per capita GDP captures the level of economic development, while industrial structure sophistication reflects the degree of industrial upgrading. Urbanization level measures the concentration of population and economic activity. Cross-border logistics

support capacity proxies the quality of logistics infrastructure and supporting services, and R&D investment intensity, measured as R&D expenditure relative to GDP, reflects regional innovation capability.

4. Data and descriptive statistics

4.1. Data processing

To reduce the influence of extreme observations, Industrial Structure Sophistication (ISU) and Urbanization Level (UL) are winsorized at the 1st and 99th percentiles. Furthermore, logarithmic transformations are performed for International Logistics Trade Efficiency (ILTE), Resource Allocation Efficiency (RAE), Digital Inclusive Finance (DIF), Per capita GDP (PGDP), Cross-border Logistics Support capacity (CLS), and R&D Investment intensity (RDI). These transformations help mitigate potential heteroskedasticity and enhance the comparability of variables measured on different scales. All transformed variables are employed in the subsequent empirical analysis, and their definitions are reported in Table 4.

Table 4. Variable definition table

type of variable	Variable Name	symbol	variable declaration
explained variable	Efficiency of international logistics and trade	ILTE	Super-efficiency DEA calculation results
Core Explanatory Variable	The level of coordinated development between green finance and digital-intelligent supply chains	D	Calculation results of the coupling coordination degree model
metavariable	Resource allocation efficiency	RAE	The ratio of regional GDP to the total number of employed individuals is expressed as its natural logarithm.
metavariable	Digital Inclusive Finance	DIF	The Digital Inclusive Finance Index developed by the Digital Finance Research Center at Peking University uses the natural logarithm of the relevant values.
controlled variable	per capita GDP	PGDP	Natural logarithm of the ratio of regional gross domestic product to the total population at the end of the year
	The industrial structure is becoming more advanced.	ISU	The proportion of the added value of the tertiary sector to that of the secondary sector
	Level of urbanization	UL	The proportion of the urban population to the total population
	Cross-border logistics support capabilities	CLS	The proportion of fixed asset investment to the regional GDP is expressed as its natural logarithm.
	Research and Development Investment Intensity	RDI	The ratio of R&D expenditure to regional GDP is expressed as its natural logarithm.

4.2. Data sources and descriptive statistics

4.2.1. Data sources

This study constructs a balanced panel dataset of 13 cities in the Beijing–Tianjin–Hebei (BTH) region over the period 2013–2024. The data are obtained from multiple authoritative sources, including the Wind Database, GTA (Guotai'an) Database, various China Statistical Yearbooks (Urban, Science and Technology, and Regional Economic), as well as provincial statistical yearbooks for Beijing, Tianjin, and Hebei. Additional data on digital economy, technological innovation, and logistics development are supplemented from the National Bureau of Statistics of China and other official statistical bulletins to ensure data completeness and consistency.

4.2.2. Descriptive statistics

Table 5 presents the descriptive statistics of the main variables. The results show considerable variation in International Logistics Trade Efficiency (ILTE), the synergy index (D), Resource Allocation Efficiency (RAE), and Digital Inclusive Finance (DIF), indicating pronounced heterogeneity across cities in the Beijing–Tianjin–Hebei region in terms of logistics performance, financial–digital development, and resource allocation efficiency. The control variables also exhibit substantial dispersion, reflecting notable cross-city differences in economic development, industrial upgrading, urbanization, logistics infrastructure, and innovation capacity. Overall, these patterns highlight significant regional heterogeneity in the sample and provide a solid empirical foundation for the subsequent analysis.

Table 5. Descriptive statistical analysis

variable	Sample Size	mean	standard deviation	least value	crest value
ILTE	156	-0.589	0.556	-1.953	1.258
D	156	0.455	0.09	0.287	0.74
D_{it}×$Trend_t$	156	2.708	1.997	0	7.775
RAE	156	4.051	0.327	3.268	4.997
DIF	156	5.411	0.298	4.734	5.952
PGDP	156	10.88	0.509	9.954	12.338
ISU	156	1.531	1.077	0.576	5.69
UL	156	0.606	0.14	0.315	0.938
CLS	156	-0.146	0.462	-1.822	0.371
RDI	156	-4.668	1.514	-10.271	-2.368

4.3. Model construction

To empirically examine the impact of the synergistic development between green finance and digital–intelligent supply chains on international logistics trade efficiency, this study specifies the following baseline regression model as Equation (6):

$$lnILTE_{it} = \alpha + \beta_1 D_{it} + \beta_2 (D_{it} \times Trend_t) + \sum \gamma_k Control_{kit} + \mu_i + \varepsilon_{it} \quad (6)$$

where: i and t index cities and years, respectively. $lnILTE_{it}$ denotes the natural logarithm of international logistics trade efficiency in city i at time t. D_{it} measures the level of synergistic development between green finance and digital–intelligent supply chains. $D_{it} \times Trend_t$ is an interaction term between the synergy index and a linear time trend, designed to capture potential time-varying effects of synergistic development. $Control_{kit}$ is a vector of control variables, including Per capita GDP (PGDP), Industrial Structure Upgrading

(ISU), Urbanization Level (UL), Cross-border Logistics Support capacity (CLS), and R&D Investment intensity (RDI). α is the intercept term. β_1 and β_2 are the parameters of interest, while γ_k is the coefficient vector associated with the control variables. μ_i captures unobserved time-invariant city-specific effects, and ε_{it} is the idiosyncratic error term.

From a theoretical perspective, the synergistic development between green finance and digital–intelligent supply chains is expected to have a dynamic and evolving impact on international logistics trade efficiency. As green finance matures, digital technologies diffuse, and interregional coordination improves, the marginal effect of synergy is likely to increase over time.To capture this dynamic feature, this study introduces an interaction term between the synergy index and a linear time trend. This specification allows the effect of $(D_{it} \times Trend_t)$ to vary over time, thereby capturing potential temporal heterogeneity in its impact. Compared with year fixed effects, which mainly control for common macroeconomic shocks, the interaction approach more directly reflects the evolving marginal effect of synergistic development over the sample period.

5. Measurement of the synergistic development level and empirical analysis

5.1. Measurement and analysis of the synergistic development level between green finance and digital–intelligent supply chains in the Beijing–Tianjin–Hebei region

5.1.1. Temporal evolution analysis

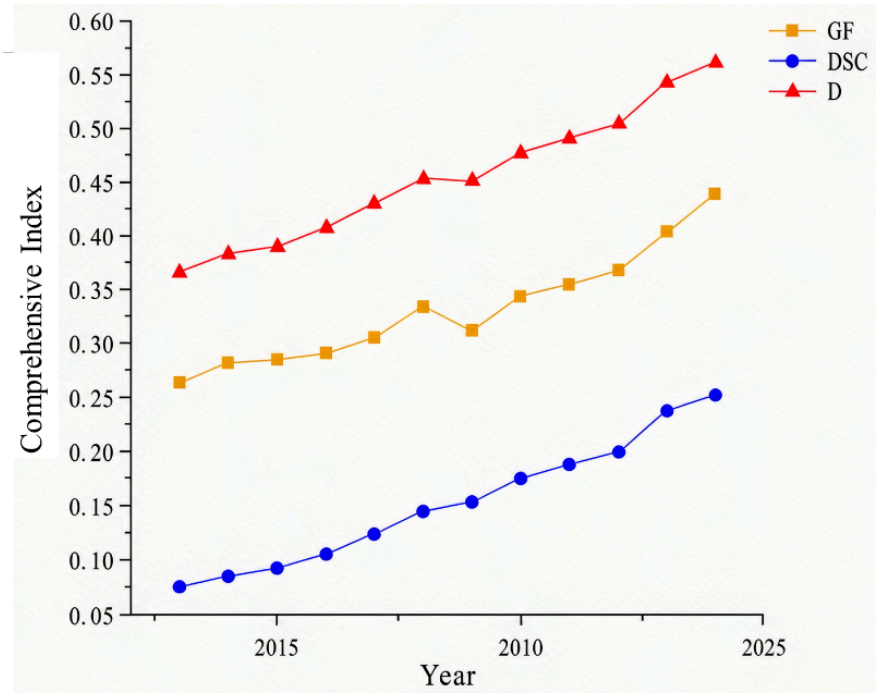

Figure 2. Evolution trends of green finance, digital and intelligent supply chains, and collaborative development levels in the Beijing-Tianjin-Hebei region (2013–2024)

Note: The image was drawn by the author based on research data results.

Figure 2 illustrates the evolution of Green Finance (GF), Digital–intelligent Supply Chains (DSC), and their synergistic development level (D) in the Beijing–Tianjin–Hebei region from 2013 to 2024. Overall, all three indicators show a sustained upward trend, indicating continuous improvement in both green finance and

digital–intelligent supply chain development, as well as strengthening interaction between the two systems. Specifically, the green finance index increased from 0.264 in 2013 to 0.439 in 2024, while the DSC index rose from 0.076 to 0.252 over the same period. Although both indicators exhibit steady growth, the DSC index shows a more pronounced increase, reflecting the rapid diffusion of digital technologies and the upgrading of supply chain intelligence. Against this backdrop, the synergy index increased from 0.366 to 0.562, showing a clear upward trend. Notably, growth accelerated after around 2020, suggesting a shift from parallel development toward deeper integration and stronger system interdependence.

5.1.2. Analysis of regional differences

Figure 3 illustrates the spatiotemporal distribution of the synergistic development level between green finance and digital–intelligent supply chains across cities in the Beijing–Tianjin–Hebei region from 2013 to 2024. Overall, coordinated development has improved steadily across all cities; however, significant regional disparities remain, exhibiting a clear hierarchical structure with leading core cities and lagging peripheral areas. Beijing consistently maintains its leading position. Cities such as Shijiazhuang, Baoding, and Langfang have experienced relatively rapid improvement and are gradually moving toward higher development tiers, while Cangzhou, Handan, and Chengde remain in lower stages with slower progress. Tianjin does not exhibit a clear advantage in synergistic development. This may be related to an imbalance between relatively advanced green finance and comparatively weaker digital–intelligent supply chain development, which limits overall coordination between the two systems. Overall, the spatial pattern shows a gradual diffusion from core cities to surrounding areas, although pronounced regional heterogeneity persists, indicating that further improvement in inter-city coordination is still needed.

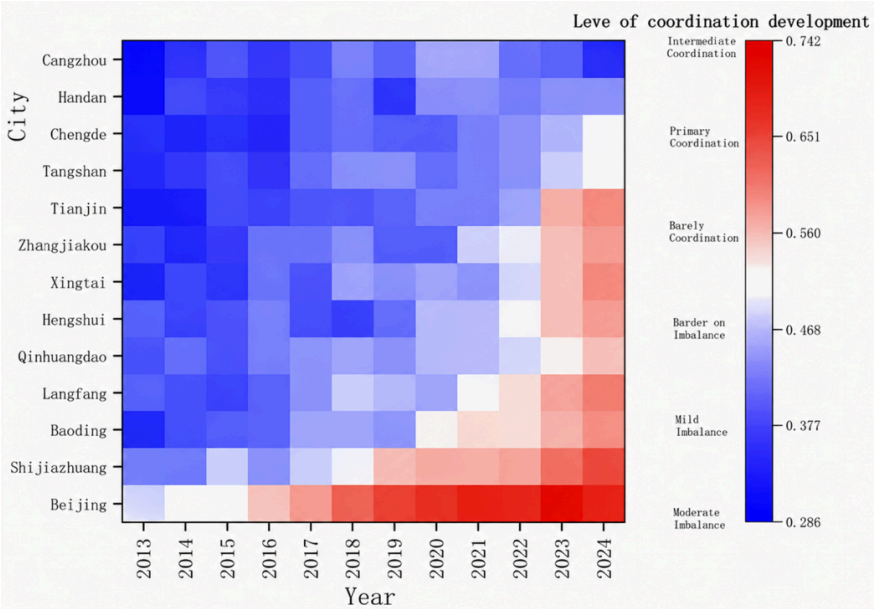

Figure 3. Spatial-temporal distribution heatmap of the coordinated development level between the Beijing-Tianjin-Hebei regional systems (2013–2024)

Note: The image was drawn by the author based on research data results.

5.2. The impact of synergistic development between green finance and digital–intelligent supply chains on international logistics trade efficiency

5.2.1. Baseline regression results

Table 6. Benchmark regression results

variable	（1）	（2）	（3）	（4）	（5）
D	-0.811	-0.806	-0.684	-0.808	-0.934
	(-1.07)	(-1.07)	(-0.93)	(-1.06)	(-1.27)
D_{it}×$Trend_t$	0.117***	0.112***	0.101***	0.111***	0.118***
	（3.94）	（3.49）	（3.05）	（2.92）	（3.24）
PGDP	-0.091	-0.087	-0.078	-0.065	-0.16
	(-0.40)	(-0.38)	(-0.34)	(-0.27)	(-0.72)
ISU		0.032	0.003	-0.007	-0.003
		（0.33）	(0.03)	(-0.07)	(-0.03)
UL			0.409	0.06	0.175
			(1.29)	(0.14)	(0.45)
CLS				0.21	0.164
				(1.57)	(1.29)
RDI					0.029***
					(2.84)
Constant	0.447	0.369	0.049	0.191	1.312
	(0.18)	(0.15)	(0.02)	(0.07)	(0.54)
Urban Fixed Effect	yes	yes	yes	yes	yes
Sample Size	156	156	156	156	156
R^2	0.847	0.8471	0.8482	0.8511	0.8538
Within R^2	0.3667	0.3672	0.3715	0.3837	0.3949

Note: Values in parentheses represent standard errors; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively. Standard errors use robust standard errors.

Table 6 reports the baseline regression results on the impact of synergistic development between green finance and digital–intelligent supply chains on international logistics trade efficiency. A stepwise approach is used for the inclusion of control variables. The results show that the interaction term between the synergy index and the time trend ($D_{it} \times Trend_t$) is positive and statistically significant at the 1% level across all specifications, indicating a robust and time-varying positive effect. In the fully specified model, the coefficient of $D_{it} \times Trend_t$ reaches 0.118, suggesting a clear cumulative effect. This implies that the impact of

synergistic development strengthens over time, likely driven by digital transformation, network externalities, and reduced information frictions. In contrast, the synergy level (D) is not statistically significant, indicating that its effect is primarily dynamic rather than contemporaneous. Among control variables, R&D Intensity (RDI) has a significantly positive effect at the 1% level, highlighting the role of innovation investment in enhancing logistics trade efficiency. Other control variables generally show expected signs. Overall, the results suggest that synergistic development improves international logistics trade efficiency through a dynamic and cumulative mechanism, supporting Hypothesis H1.

5.2.2. Robustness tests

5.2.2.1. Alternative measure of the explanatory variable

In the baseline regressions, the coupling coordination index (D) is used to measure the synergistic development between green finance and digital–intelligent supply chains. To address potential measurement bias arising from indicator construction, this study replaces D with an alternative proxy, namely the coordination index (T), which captures the overall coordinated development level of the two systems and is widely used in the literature.

The regression results using the alternative measure remain consistent with the baseline findings, confirming the robustness of the main conclusions.

5.2.2.2. Excluding COVID-19 shock period

Given the substantial impact of the COVID-19 pandemic on logistics, international trade, and supply chain operations during 2020–2021, this period may introduce temporary structural shocks that affect estimation accuracy. To account for this concern, the sample excludes observations from 2020–2021, and the model is re-estimated.

The results remain qualitatively unchanged, indicating that the baseline findings are not driven by pandemic-related disruptions.

5.2.2.3. Excluding the beijing sample

As the core city of the Beijing–Tianjin–Hebei region, Beijing exhibits significantly higher levels of green finance development, digital infrastructure, and technological innovation compared to other cities, which may generate sample heterogeneity and potential estimation bias.

To address this concern, Beijing is excluded from the sample, and the regressions are re-estimated. The results remain stable, further supporting the robustness of the empirical findings.

Table 7. Results of robustness tests

variable	(1) Replace the explanatory variable T	(2) Excluding years affected by the pandemic	(3) Excluding the Beijing sample
D (perhaps T)	0.325	-0.872	-0.81
	（0.714）	（0.807）	（0.79）
D_{it}×$Trend_t$	0.069**	0.121***	0.107***
	（0.032）	（0.035）	（0.039）
PGDP	-0.077	-0.124	-0.068
	(0.252)	(0.231)	(0.244)

Table 7. Continued

ISU	-0.005	-0.042	0.05
	(0.098)	(0.117)	(0.115)
UL	0.308	0.067	0.074
	(0.375)	(0.456)	(0.413)
CLS	0.168	0.153	0.082
	(0.147)	(0.149)	(0.129)
RDI	0.026***	0.030**	0.031***
	(0.01)	(0.012）	（0.011）
Constant	-0.048	1.005	0.242
	（2.74）	（2.491）	（2.658）
Urban Fixed Effect	yes	yes	yes
Sample Size *N*	156	130	144
R^2	0.853	0.84	0.851

Note: Values in parentheses represent the robust standard error; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 7 reports the robustness test results. The findings show that, across all specifications—using an alternative coordination index (T), excluding the COVID-19 period (2020–2021), and removing the Beijing sample—the coefficient of the interaction term ($D_{it} \times Trend_t$) remains positive and statistically significant at the 5% level or above. Specifically, the estimated coefficient of $D_{it} \times Trend_t$ is 0.069 (5% level) when replacing the explanatory variable, 0.121 (1% level) after excluding the pandemic period, and 0.107 (1% level) when excluding Beijing. The sign, magnitude, and significance of the coefficient remain broadly consistent with the baseline results. Overall, these findings indicate that the positive impact of synergistic development on international logistics trade efficiency is robust to alternative variable definitions, sample adjustments, and external shocks, confirming the stability of the baseline results.

5.2.3. Endogeneity test

There may exist a potential reverse causality between the synergistic development of green finance and digital–intelligent supply chains and international logistics trade efficiency. On the one hand, higher levels of synergistic development may improve logistics trade efficiency; on the other hand, improvements in logistics efficiency may further facilitate the agglomeration of green finance resources and accelerate the digital transformation of supply chains, thereby generating endogeneity concerns.

To address this issue, following the approach commonly adopted in the literature, this study uses the first-order lag of the synergistic development index as an instrumental proxy in the regression analysis to mitigate potential reverse causality.

Table 8. Results of endogeneity tests

variable	(1) The explanatory variable lagged by one period
$D_{i,t-1}$	-0.78
	（0.849）
$D_{i,t-1} \times Trend_t$	0.116***
	（0.042）
PGDP	-0.112
	（0.245）
ISU	0.037
	（0.097）
UL	0.436
	（0.442）
CLS	0.197
	（0.14）
RDI	0.023**
	（0.01）
Constant	0.513
	（2.742）
Urban Fixed Effect	yes
Sample Size *N*	143
R^2	0.8677

Note: Values in parentheses represent the robust standard error; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 8 reports the endogeneity test results. The coefficient of the interaction term between the lagged synergistic development index and the time trend ($D_{i,t-1} \times Trend_t$) is 0.116 and significant at the 1% level, with the same sign as the baseline results. The estimated magnitude is close to the benchmark coefficient of 0.118, suggesting that the positive effect of synergistic development on international logistics trade efficiency remains stable after accounting for potential endogeneity. Overall, the results indicate that endogeneity does not materially bias the main findings, confirming the reliability of the baseline estimates.

5.3. Mechanism test: the mediating role of resource allocation efficiency and digital inclusive finance

To further explore the transmission channels through which the synergistic development of green finance and digital–intelligent supply chains enhances international logistics trade efficiency, this study focuses on two mechanisms: Resource Allocation Efficiency (RAE) and Digital Inclusive Finance (DIF).Green finance improves capital allocation efficiency by directing financial resources toward more productive sectors, while digital–intelligent supply chains enhance information flow and coordination through digital technologies, thereby reducing resource misallocation. In addition, digital inclusive finance expands the coverage of financial services, alleviates financing constraints, and provides more accessible financial support for logistics and trade activities. Based on this framework, this paper empirically tests these two channels using RAE and DIF as mediating variables. The measurement model for mediating variable are shown in Equations (7) and (8).

5.3.1. Model setup

$$lnRAE_{it} = \alpha_0 + \alpha_1 D_{it} + \alpha_2 \ (D_{it} \times Trend_t) \ + \alpha_3 X_{it} + \mu_i + \varepsilon_{it} \tag{7}$$

where: $lnRAE_{it}$ represents the efficiency of resource allocation; D_{it} represents the level of synergistic development between green finance and digital-intelligent supply chains; $D_{it} \times Trend_t$ represents the interaction term between synergy development level and time trend; X_{it} is a control variable; μ_i denotes urban fixed effects; ε_{it} and is the random disturbance term.

$$lnDIF_{it} = \beta_0 + \beta_1 D_{it} + \beta_2 (D_{it} \times Trend_t) + \beta_3 X_{it} + \mu_i + \varepsilon_{it} \tag{8}$$

where: $lnDIF_{it}$ represents the development level of digital inclusive finance; the definitions and formulas for the remaining variables are consistent with those in Equation (7).

5.3.2. Result analysis

Table 9. Results of mechanism testing

variable	Benchmark Regression ILTE	RAE	DIF
D	-0.934	-0.703*	-0.267
	(0.737)	（0.378）	（0.323）
D_{it}×$Trend_t$	0.118***	0.086***	0.056**
	(0.037)	（0.028）	（0024）
Constant	1.312	-0.594	-1.231
	(2.452)	（2.245）	（1.957）
Urban Fixed Effect	yes	yes	yes
N	156	156	156
R^2	0.8538	0.9196	0.9385

Note: Values in parentheses represent the robust standard error; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 9 reports the mechanism test results for resource allocation efficiency and digital inclusive finance. The coefficient of the interaction term ($D_{it} \times Trend_t$) is positive and statistically significant in both models. Specifically, in the resource allocation efficiency model, the coefficient is 0.086 and significant at the 1% level, while in the digital inclusive finance model it is 0.056 and significant at the 5% level. These results indicate that the dynamic effect of synergistic development extends beyond international logistics trade efficiency to improvements in both resource allocation and financial inclusion. Green finance improves resource allocation efficiency by directing capital toward more productive uses, while digital–intelligent supply chains enhance factor allocation through improved information sharing and coordination. In addition, digital inclusive finance expands financial access and alleviates financing constraints for logistics-related activities. Overall, resource allocation efficiency and digital inclusive finance serve as important transmission channels through which synergistic development affects international logistics trade efficiency, supporting Hypotheses H2 and H3.

5.4. Heterogeneity analysis

5.4.1. Heterogeneity based on the development level of green finance

To examine whether green finance development affects the synergistic impact, the sample is divided into high and low groups based on the mean value of the Green Finance Index, and separate regressions are conducted. The results are reported in Columns (1) and (2) of Table 10. In the high green finance group, the coefficient of the interaction term ($D_{it} \times Trend_t$) is 0.203 and significant at the 10% level, while it is not statistically significant in the low green finance group. This indicates that higher green finance development strengthens financial support for digital transformation and logistics upgrading, thereby enhancing the transmission of synergistic effects to international logistics trade efficiency. In contrast, weaker financial systems may limit the realization of such benefits due to constrained funding capacity.

5.4.2. Heterogeneity based on the development level of digital–intelligent supply chains

Table 10. Results of heterogeneity analysis

variable	Level of Green Finance		Level of Digital and Intelligent Supply Chain Management	
	High Green Finance Group	Low Green Finance Group	High-Level Intelligent Supply Chain Group	Low-Number Intelligent Supply Chain Group
	(1)	(2)	(3)	(4)
D	-2.801	-0.049	-1.267	-0.766
	（2.693）	（0.651）	（0.848）	（0.563)
$D_{it} \times Trend_t$	0.203*	0.014	0.105**	0.075
	(0.105)	(0.035）	（0.051）	（0.051）
Urban Fixed Effect	yes	yes	yes	yes
N	78	78	78	78
R^2	0.855	0.965	0.893	0.953

Note: Values in parentheses represent the robust standard error; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

A similar grouping strategy is applied based on the digital–intelligent supply chain index. The results in Columns (3) and (4) of Table 10 show that $D_{it} \times Trend_t$ is 0.105 and significant at the 5% level in the high-development group, while it is insignificant in the low-development group. This suggests that higher levels of digital–intelligent supply chain development improve data sharing, coordination, and resource matching, enabling more efficient allocation of green finance to logistics and trade activities. By contrast, weaker digital infrastructure and coordination capacity in lagging regions hinder the integration of financial and logistics systems, limiting the realization of synergistic effects.

Overall, the synergistic effect of green finance and digital–intelligent supply chains on international logistics trade efficiency exhibits clear heterogeneity. The positive impact is primarily concentrated in regions with relatively well-developed green finance systems and more advanced digital–intelligent supply chain infrastructure. These findings suggest that the realization of synergistic gains depends not only on the availability of green financial resources, but also on the support of adequate digital infrastructure. In this sense, green finance and digital–intelligent supply chains act as complementary foundations, jointly underpinning improvements in international logistics trade efficiency.

6. Conclusion and policy implications

6.1. Conclusion

International logistics trade efficiency is an important indicator of regional openness and development quality, while the synergistic development of green finance and digital–intelligent supply chains provide a new driver for the green and digital upgrading of logistics systems. Based on panel data from 13 cities in the Beijing–Tianjin–Hebei region, this study examines the impact and mechanisms of this synergy. The main findings are as follows.

(1) Green finance, digital–intelligent supply chains, and their synergy all show a sustained upward trend, indicating a shift from independent development to deeper integration. However, regional disparities remain, with core cities leading and peripheral cities lagging, suggesting the need for improved regional coordination.

(2) Synergistic development significantly enhances international logistics trade efficiency, with a clear dynamic and cumulative effect. This impact strengthens over time alongside financial deepening and digital integration. The effect is more pronounced in regions with higher development levels, indicating significant heterogeneity.

(3) Resource allocation efficiency and digital inclusive finance act as key transmission channels. Their improvement facilitates capital allocation, expands financial access, and supports the digital transformation of logistics firms, thereby enhancing international logistics trade efficiency.

6.2. Policy implications

Based on the above findings, several policy implications can be drawn.

(1) Given persistent regional disparities in the coordinated development of green finance and digital–intelligent supply chains in the Beijing–Tianjin–Hebei region, regional coordination should be further strengthened. Policy efforts should leverage Beijing's advantages in innovation and financial resource concentration to promote knowledge spillovers, technology transfer, and resource sharing with Tianjin and Hebei, while providing targeted support to less-developed areas to reduce regional imbalances.

(2) The green finance system should be further improved by expanding instruments such as green loans, green bonds, and green funds, and by increasing capital allocation to green logistics, smart warehousing, and digital transportation. At the same time, the application of digital technologies, including big data, artificial intelligence, and the Internet of Things, should be deepened to enhance supply chain digitalization. Leading regions should serve as demonstration areas, while lagging regions should focus on strengthening digital infrastructure and green finance capacity.

(3) Greater attention should be given to the complementary role of resource allocation efficiency and digital inclusive finance. Policymakers should improve digital financial infrastructure, expand inclusive finance coverage, and enhance capital allocation efficiency toward green logistics and supply chain transformation. In addition, integration among logistics systems, financial institutions, and digital platforms should be strengthened to improve data sharing, reduce transaction costs, and facilitate efficient resource flows, thereby supporting improvements in international logistics trade efficiency.

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