



Impact Mechanisms of Digital Trade on the Development of Open Economies: Evidence from the Yangtze River Delta Region

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Abstract. As an offshoot of the digital economy, digital trade fuels socioeconomic growth and supports China's rise as a trading power. The Yangtze River Delta (YRD), one of the nation's most vibrant and open regions, has led digital-trade expansion since 2013. Using data from 2013 to 2022, we first construct an entropy weighted TOPSIS index to measure digital-trade development. We then estimate its impact on open-economy growth with an OLS baseline model and explore two pathways, namely tertiary industry upgrading and technological innovation, through mediation model analysis. Findings are threefold. First, YRD digital trade increased steadily over the decade, yet provincial gaps persist, and Zhejiang, Jiangsu and Shanghai outperform Anhui. Second, stronger digital-trade activity enlarges the region's open economy. Third, service-sector growth and innovation progress partially transmit this positive relationship. These results provide a basis for policy measures that can leverage digital trade more effectively and advance regional openness.

Keywords: digital trade; Yangtze River Delta; TOPSIS; mediation effect

1 Introduction

In today's flourishing digital economy, digital transformation driven by information and communication technologies is profoundly reshaping economic development models and trade structures across countries and regions. On the one hand, digital trade utilizes digital information technologies to enhance the convenience and timeliness of cross-border transactions, simplifying complex trade processes and reducing international transaction costs. On the other hand, it empowers traditional trade models by optimizing processes and promoting the digital transformation of conventional trade activities.

Although digital trade remains in its early stages, it has introduced new growth opportunities for the high-quality development of China's international trade. In recent years, the Yangtze River Delta (YRD) region has seen rapid growth in digital trade, which has had far-reaching effects on the regional economy and society. Therefore,

measuring digital trade levels and exploring the mechanisms by which digital trade influences the development of an open economy using the YRD as a case study is of strong practical significance and reference value.

The contribution of this study can be summarized as follows: First, it offers a new analytical perspective for measuring regional digital trade development. We start by clearly defining the concept of digital trade and then conduct an innovative investigation into the mechanisms through which digital trade influences the development of an open economy. Second, the selected set of indicators for measurement synthesizes those used by existing experts and scholars, creating an evaluation model that is highly comparable and better tailored to the regional context. Finally, from the perspective of regional economic development, we use data on digital trade development in the YRD to provide practical recommendations. The YRD's digital trade has shown resilient growth despite global economic downturn pressures, offering valuable lessons for other regions in China. From a macro perspective, with the YRD's digital trade flourishing and maintaining a high level of developmental quality, this study provides insights for other regions to develop digital trade and expand their open economies.

2 Literature Review

2.1 Definition about Digital Trade

Weber (2010) was among the pioneers to introduce the concept of digital trade, defining it as the exchange of products or services that are delivered through digital channels, specifically over the internet. This definition laid the foundation for subsequent research into the digital economy and its impact on global trade networks^[1]. In 2012, the U.S. Bureau of Economic Analysis introduced the concept of digitally delivered services trade, highlighting the growing importance of digitally enabled services in international trade^[2]. In China, Xiong (2010) first discussed digital trade in his book *Digital and Business*, defining it as an innovative global business model built on internet-based digital information exchange technologies^[3]. In 2013, the United States International Trade Commission (USITC) defined digital trade in its report *Digital Trade in the U.S. and Global Economies, Part I* as both domestic and international commercial activities facilitated through the internet^[4]. These activities span four broad categories: digital content, social media, search engines, and various other products and services. This definition has been widely adopted in international research and policy discussions. A 2019 white paper by the China Academy of Information and Communications Technology (CAICT) clarified that digital trade arises from the rapid growth of the digital economy. It highlights the critical role of information and communication technologies in enabling trade, encompassing both the trade of physical goods and services delivered digitally through information networks^[5]. Additionally, Jia (2022) proposed pilot measurements of digital trade using an integration ratio method to calculate actual digitally delivered services, focusing on digitally deliverable services as the core of digital trade measurement^[6].

2.2 Methods for Measuring Digital Trade Development Levels

Several studies have constructed indicator systems to evaluate the development level of digital trade. Zhang et al. (2023) developed a digital trade development evaluation system based on five primary indices: digital trade potential, infrastructure quality, digital market accessibility, trade structure, and environmental security. Using these indices, they measured digital trade development levels across various Chinese cities, finding a clear nationwide improvement in digital trade, with the eastern region exhibiting a strong development trend^[7]. Wang et al. (2023) focused on four aspects—digital infrastructure, trade scale, policy environment, and innovation inputs—to construct a measurement system for digital trade development^[8]. They applied this system to assess the digital trade development levels and gains of major trading nations. Li et al. (2024) proposed a comprehensive digital trade evaluation index system for Zhejiang Province, encompassing four key dimensions: digital infrastructure inclusiveness, trade scale, trade potential, and digital trade capability^[9]. They employed an entropy-weighted coupling coordination model to measure and evaluate the province's digital trade development over the past five years.

2.3 Empirical Studies on Digital Trade and Economic Development

An emerging strand of research examines the economic impacts of digital trade. Liu et al. (2024) developed a digital trade index system and employed a mediation effect model to analyze the impact of digital trade on industrial structure upgrading and the high-quality development of manufacturing in the Yangtze River Delta (YRD). The results showed that digital trade positively contributes to high-quality manufacturing development and industrial upgrading in the region^[10]. Yuan (2022) employed a baseline regression model to empirically analyze the influence of digital trade on the upgrading of China's manufacturing structure. The study found a bidirectional promotive relationship between digital trade and the upgrading of the manufacturing structure^[11]. Similarly, Tang (2023) analyzed digital trade development in the Yangtze River Economic Belt and built an evaluation system. Using panel data and a fixed-effects model, the study examined the impact of digital trade on the international competitiveness of manufacturing in that region. The findings indicated that digital trade helps enhance the international competitiveness of manufacturing in the Yangtze River Economic Belt^{[12]-[13]}.

In summary, the USITC's definition of digital trade has been widely adopted in the literature, and many studies on measuring digital trade levels focus on regional and national competitiveness in the context of globalization. China is currently at a critical stage of high-quality economic development and industrial transformation. However, there is relatively little research examining the mechanisms and empirical evidence of how digital trade affects the development of an open economy, particularly using the YRD region as an example. Therefore, this paper seeks to fill this gap by analyzing the mechanisms through which digital trade influences the development of an open economy and by conducting an empirical evaluation of digital trade development levels and their effects.

3 Methodology

3.1 Hypotheses

3.1.1. Hypothesis 1: Digital trade Promotes the Expansion of a Region'S Open Economy Scale by Stimulating the Development of the Tertiary (Services) Industry.

Digital trade plays a key role in promoting the development of the tertiary sector, especially in industries such as information transmission, software, and information technology services. First, digital trade introduces two new types of production factors: data and digital technology. It enriches the content and forms of services within the tertiary industry by creating digital platforms that better connect products with consumers. As a driving force behind modern service industry growth, digital trade enables the deep integration of technologies such as 5G, artificial intelligence, and blockchain with regional economic development, thus facilitating economic transformation. By harnessing new productivity forms, digital trade advances the digital economy and significantly enhances the efficiency of regional economic and trade activities.

Digital trade also generates new market demand and, while empowering and transforming traditional industries, provides a continuous stream of momentum and new growth points for the service sector. Second, as the market size of the tertiary industry grows, the scale of the open economy expands. As digital trade flourishes, more enterprises engage with regional digital platforms to participate in international production and collaboration through digital means. These platforms empower businesses, reduce costs, and yield greater economic benefits. This process stimulates the expansion of the tertiary industry, particularly in sectors such as software and IT services, commercial services, and other related industries. As the market size of the tertiary sector increases, the level of economic informatization rises, and the intensity of domestic and international linkages strengthens. The degree of a region's external linkages is a key factor in measuring the scale of an open economy, thus changes in the size of the tertiary sector directly influence the expansion of a region's open economy scale. Accordingly, we propose the hypothesis that digital trade promotes the expansion of a region's open economy scale by stimulating the development of the tertiary (services) industry.

3.1.2. Hypothesis 2: Digital trade, Through Promoting Technological Innovation, Leads to an Expansion of the Region'S Open Economy Scale.

Digital trade is an integral part of the digital economy, and its development is heavily reliant on technological innovation and advancement. Technologies such as cloud computing, big data analytics, artificial intelligence, and blockchain have become powerful enablers of digital trade growth. By introducing new digital production methods, the rise of digital trade has led traditional foreign trade enterprises to demand more efficient, secure, and personalized products and services. To remain competitive in international markets, firms increasingly engage in technological innovation, leveraging digital technologies to meet evolving market needs. Additionally, the vast amounts of data generated through digital trade serve as a crucial resource for compa-

nies to enhance product design, improve service processes, and gain valuable market insights, making data a key driver of technological innovation.

Technological progress, in turn, is a major force driving the expansion of an open economy. The growth of digital trade stimulates the technology market, while the R&D and application of cutting-edge technologies contribute further to the scaling of the open economy. Technological innovation—through automation and intelligent production systems—can optimize supply chain management, significantly increase production efficiency, and reduce costs, enhancing enterprises' competitiveness in international trade. Moreover, the development of information technology, blockchain, and the Internet of Things optimizes trade processes, facilitates trade liberalization, and enhances the ease with which goods and services flow across borders.

Technological innovation has also given rise to new business models such as cross-border e-commerce, platform economies, and the sharing economy, which deepen a region's external economic linkages and expand its economic scale, thus contributing to more open economic development. Furthermore, technological innovation fosters international exchange and cooperation, allowing regions to strengthen collaboration and build a more open and inclusive economic environment. Accordingly, we propose the hypothesis that digital trade, through promoting technological innovation, leads to an expansion of the region's open economy scale. The impact mechanism diagram is as follows Figure 1.

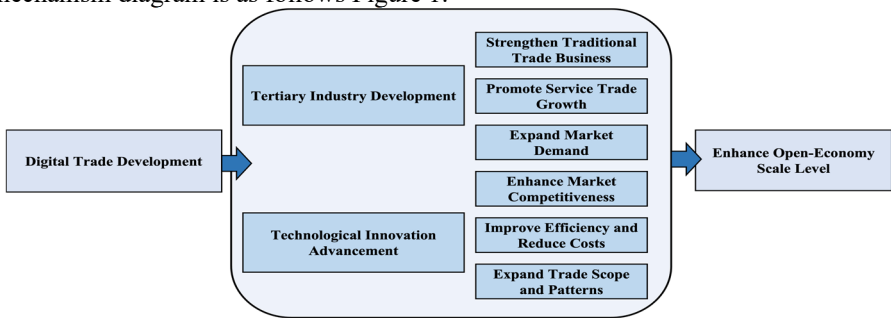


Fig. 1. The Mechanism Pathway of Digital Trade Development in Enhancing the Level of Open-Economy Scale.

3.2 Measurement of Digital Trade Development

3.2.1. Evaluation Metrics for Digital Trade Level.

The level of digital trade development is a comprehensive index that must be assessed through a multidimensional evaluation system. In 2020, amid the rapid growth of digital trade, the IMF, OECD, and WTO collaboratively released the first edition of the Handbook on Measuring Digital Trade (with a second edition released in 2023). This handbook divides digital trade into two broad categories: digitally ordered and digitally delivered, and it proposes methods for measuring digital trade. It currently represents one of the most authoritative approaches to measuring national digital trade development. In this framework, digitally ordered trade essentially refers to international e-commerce (a subset of total e-commerce), while digitally delivered trade refers

to international trade transactions delivered via computer networks, covering only services.

However, due to difficulties in obtaining data for certain indicators, we draw on the methods of Yao (2020) [14] and Wang et al. (2023) [8] and synthesize insights from existing research to construct a comprehensive evaluation system for measuring the digital trade development level of the YRD’s three provinces and one municipality. Our indicator system encompasses five dimensions: digital trade infrastructure, digital trade technological infrastructure, digital trade market scale, digital trade potential, and digital trade environment security. We select 13 secondary indicators under these five dimensions, as shown in Table 1. Based on this, we employ the entropy weight method to determine the weight of each secondary indicator, and then use the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) method to calculate a composite development score for each region.

Table 1. Indicators for Measuring Digital Trade Development Level in the Yangtze River Delta.

Primary Indicator	Secondary Indicator	Unit
Digital Trade Infrastructure	Q1: Mobile phone users per 100 people	units per 100 persons
	Q2: Higher education recipients per 10,000 people	persons
Digital Trade Technological Infrastructure	Q3: Internal expenditure on R&D	100 million yuan
	Q4: R&D personnel	10,000 persons
	Q5: Information transmission, software & IT services industry	100 million yuan
Digital Trade Market Scale	Q6: Scientific research & technical services industry	100 million yuan
	Q7: Total postal and telecommunications business volume	100 million yuan
	Q8: Gross regional product (GDP)	100 million yuan
Digital Trade Potential	Q9: Per capita disposable income	yuan
	Q10: Total import-export trade volume	100 million USD
	Q11: Number of domestic patent applications accepted	count
Digital Trade Environment Security	Q12: Public security budget expenditure (regional)	100 million yuan
	Q13: Science and technology budget expenditure (regional)	100 million yuan

Based on the five dimensions and 13 secondary indicators outlined above, we can preprocess the data and conduct a measurement analysis of the digital trade development level across the three provinces and one municipality in the YRD over the most recent 10-year period

3.2.2. Analysis of Digital Trade Development Level in the Yangtze River Delta.

Specific steps of the measurement and analysis process are as follows.

(1) Standardization of the Imported Matrix

The first step is to check whether any negative values exist in the imported matrix. If negative values are found, standardization is required. This study evaluates 40 units (comprising three provinces and one municipality in the Yangtze River Delta (YRD))

over the past decade, with 13 evaluation indicators. The positive matrix after normalization is provided below:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \quad (1)$$

Each indicator in the standardized matrix is represented as follows:

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^n x_{ij}^2}} \quad (2)$$

Next, we check for any negative values in the matrix. If found, we standardize matrix X to obtain the new matrix using the formula:

$$\tilde{z}_{ij} = \frac{x_{ij} - \min\{x_{1j}, x_{2j}, \dots, x_{nj}\}}{\max\{x_{1j}, x_{2j}, \dots, x_{nj}\} - \min\{x_{1j}, x_{2j}, \dots, x_{nj}\}} + 0.01 \quad (3)$$

(2) Calculation of Proportions

For each indicator j the proportion of sample i within the total for that indicator is computed. This proportion is treated as the probability used in the relative entropy calculation. With 40 evaluation units and 13 digital trade indicators, the non-negative matrix derived in the previous step is:

$$\tilde{Z} = \begin{bmatrix} \tilde{z}_{11} & \tilde{z}_{12} & \cdots & \tilde{z}_{1m} \\ \tilde{z}_{21} & \tilde{z}_{22} & \cdots & \tilde{z}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{z}_{n1} & \tilde{z}_{n2} & \cdots & \tilde{z}_{nm} \end{bmatrix} \quad (4)$$

We then compute the probability matrix P , where each element P_{ij} is calculated using the following formula:

$$P_{ij} = \frac{\tilde{z}_{ij}}{\sum_{i=1}^n \tilde{z}_{ij}} \quad (5)$$

Naturally, the sum of probabilities for each indicator should equal 1.

(3) Calculation of Entropy and Information Utility Values

For the 13 indicators, we calculate the information entropy and information utility values. After normalization, we obtain the entropy weight for each indicator. The formula for computing information entropy is:

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^n p_{ij} \ln(p_{ij} + 0.01) (j=1, 2, \dots, m) \tag{6}$$

The information utility value is defined as $d_j = 1 - e_j$, where a higher utility value indicates more useful information. The information utility values are normalized, yielding the entropy weights:

$$W_j = d_j / \sum_{j=1}^m (j = 1, 2, \dots, m) \tag{7}$$

From this, we can determine the weight of each of the 13 secondary indicators in the overall evaluation model, as shown in Table 2 below.

Table 2. Weights of 13 Indicators for Digital Trade Development Measurement (%)

Indicator	Q1	Q2	Q3	Q4	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13
Weight	2.44	0.52	6.75	11.6	10.48	10.48	8.88	17.21	5.77	5.25	10.76	11.9	5.08	3.30
(%)				2								4		

(4) Computing the Comprehensive Scores

Next, we apply the entropy weighted TOPSIS model to the standardized matrix of size (n=40, m=13):

$$Z = \begin{bmatrix} Z_{11} & Z_{12} & \dots & Z_{1m} \\ Z_{21} & Z_{22} & \dots & Z_{2m} \\ \dots & \dots & \ddots & \vdots \\ Z_{n1} & Z_{n2} & \dots & Z_{nm} \end{bmatrix} \tag{8}$$

Let Max: $Z^+ = (Z_1^+, Z_2^+, \dots, Z_m^+)$, where $D_i^+ = \sqrt{\sum_j^m (Z_j^+ - z_{ij})^2}$.

Let Min: $Z^- = (Z_1^-, Z_2^-, \dots, Z_m^-)$, where $D_i^- = \sqrt{\sum_j^m (Z_j^- - z_{ij})^2}$.

The unnormalized score for each evaluation unit is calculated by computing the distance from the ideal and anti-ideal solutions:

$$S_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{9}$$

which can be normalized as:

$$\widetilde{S}_i = S_i / \sum_{i=1}^n S_i \quad (10)$$

The scores for digital trade development in the YRD region from 2013 to 2022 are shown in Table 3. For better presentation, the data are rounded to the nearest whole number.

Table 3. Digital Trade Development Scores for the Yangtze River Delta (2013-2022).

Year	Jiangsu	Anhui	Shanghai	Zhejiang	Average
2013	2.37	0.1	1.92	2.83	1.805
2014	2.48	0.17	2.12	3.59	2.09
2015	2.72	0.23	2.38	4.18	2.3775
2016	2.79	0.38	2.57	3.38	2.28
2017	2.81	0.43	2.69	3.48	2.3525
2018	3.57	0.86	1.92	2.83	2.295
2019	4.23	1.35	2.12	3.59	2.8225
2020	4.98	1.69	2.38	4.18	3.3075
2021	4.02	1.14	2.57	3.38	2.7775
2022	4.09	1.35	2.69	3.48	2.9025
Average	3.406	0.77	2.336	3.492	2.501

Note: computed using MATLAB 2019b.

From the table, it is evident that Zhejiang has the highest average score of 3.49, while Anhui has the lowest average score of 0.77. Jiangsu and Shanghai rank second and third with average scores of 3.41 and 2.34, respectively. Anhui's digital trade development level is relatively low, and its economic vitality is at the bottom of the regional rankings. This indicates a disadvantage compared to other provinces and municipalities in the YRD. The data also show that there are significant differences in digital trade development levels between provinces and municipalities in the region. Additionally, the measurement results indicate that the average score for digital trade development in the YRD has increased from 1.81 in 2013 to 2.90 in 2022, reflecting significant improvement in the region's digital trade development.

In conclusion, based on the entropy-weighted method and the TOPSIS digital trade evaluation model, the results show that the digital trade development level in the YRD has generally increased, with strong momentum. However, significant disparities remain between provinces and municipalities, and the development is uneven across the region. The data from this section provide the foundation for the empirical analysis of the impact of digital trade on the open economy in the following section.

3.3 Quantify the Impact of Digital Trade on a Region's Open Economy

The above sections have already provided a comprehensive evaluation of the digital trade development level in the Yangtze River Delta (YRD) region, covering five dimensions: digital trade infrastructure, technological facilities, market size, trade potential, and digital trade environment security, for the years 2013-2022. The next part of the study continues to empirically examine the impact of digital trade development on the open economy and the transmission mechanisms in the YRD region, based on the analysis above.

An open economy is an economic system that includes the free international flow of products or production factors, the international division of labor in product production, and the redistribution of added value (Sachs et al., 2004) [15]. To some extent, The regional economic openness can be analyzed by participating in foreign trade and introducing foreign investment. Therefore, this study uses foreign trade volume as a measure of a region's open economic development level, and the foreign direct investment (FDI) and others factors as controlled variables as defined by the following formula:

$$Y_{kf} = \ln X_{it} \quad (11)$$

where Y_{kf} represents the scale of open economic development in region i at time t , and X_{it} represents the total foreign trade import and export value in region i at time t . The higher the index, the larger the scale of open economic development. This reflects not only the region's active participation in outward-oriented economic development but also its economic vitality.

3.3.1. Regression Model.

To effectively explore the impact of digital trade on regional open-economic development, the following baseline regression model is established:

$$Y_{kf} = \alpha_0 + \alpha_1 szmy_{it} + \alpha_2 \ln Tel_{it} + \alpha_3 \ln FDI_{it} + \alpha_4 \ln aGDP_{it} + \alpha_5 \ln Pg_{it} + \varepsilon_{it} \quad (12)$$

where Y represents the level of regional open-economic development, i is the region, t is the time, and ε_{it} is the error term. $\alpha_0 \sim \alpha_5$ represents the coefficients of each explanatory variable. To comprehensively measure the degree of regional economic openness and avoid errors caused by omitted variables, we consider adding Controlled Variables: Foreign Direct Investment (FDI), regional per capita GDP (aGDP), regional telecommunication development (Tel), and external economic cooperation (Pg).

3.3.2. Variables Selection.

Dependent variable: Regional open economy development level (Y). We use each region's total import and export trade volume as the indicator and take its natural logarithm (\ln) to measure the scale of the open economy. A region's total import-export volume reflects the scale of its participation in international economic cooperation and

its economic base; using the logarithmic form helps alleviate issues of heteroscedasticity and reduces the influence of outliers.

Independent variable: Digital trade development level (Szmy). The core explanatory variable is the digital trade development level of each province/city in the YRD. We use the comprehensive score measured by the entropy-weighted TOPSIS evaluation model for 2013–2022 (constructed in Section 3) as the indicator of digital trade development. This composite index encapsulates the digital trade performance of each region each year.

Control variables: To isolate the effect of digital trade and account for other factors that may influence the scale of an open economy, we include four control variables based on prior research and relevant economic reasoning:

1. **Actual foreign direct investment (FDI):** Measured as the actual utilized amount of foreign capital in the region (we use the logarithm of this value). Foreign investment can invigorate the domestic market, bring advanced technologies and management experience, and thus expand the scale of a region's open economy by strengthening linkages with global industrial chains and fostering high-quality development.
2. **Regional per capita GDP (aGDP):** Measured as per capita gross domestic product of the region (log-transformed). Per capita GDP reflects the level of socio-economic development and productivity of a region. When economic development reaches a certain level (a threshold), further increases in per capita GDP can in turn promote the development of an open economy by providing a stronger economic foundation for trade.
3. **Postal and telecommunications business volume (Tel):** Measured as the total volume of postal and telecommunication services in the region (log-transformed). A higher postal/telecom business volume indicates robust demand for communication services, frequent internal and external economic interactions, and strong economic vitality in the region. Improved information infrastructure and connectivity can make external trade linkages more convenient and reflect higher enterprise IT capabilities and innovation capacity.
4. **Number of overseas projects (Pg):** Measured as the number of overseas investment projects undertaken by the region (log-transformed). A greater number of outward investment projects signifies a higher degree of internationalization and more intensive participation in international economic exchange and cooperation, which in turn promotes related import-export activities.

4 Results

4.1 Data Analysis

The original data for all variables are sourced from local statistical yearbooks, finance and statistics departments, and through communication with provincial statistical offices for non-public data. The key indicators are shown in Table 4.

Table 4. Description of Selected Indicator Variables

Variable Type	Variable Name	Symbol	Variable Definition
Dependent Variable	Open Economic Scale	Y	Logarithm of total import-export trade volume
Independent Variable	Digital Trade Level	Szmy	Calculated using the TOPSIS method
Control Variable	Foreign Direct Investment	ln <i>FDI</i>	Logarithm of actual foreign investment
	Per Capita GDP	ln <i>aGDP</i>	Logarithm of per capita GDP
	Telecommunication Volume	ln <i>Tel</i>	Logarithm of telecommunication service volume
	Number of Foreign Projects	ln <i>Pg</i>	Logarithm of the number of foreign investment projects

Descriptive statistics of the variables, based on data analyzed using Stata, are shown in Table 5.

Table 5. Descriptive Statistics of Variables

Variable	Obs	Mean	Std.Dev.	Min	Max
ln y	40	8.019228	0.9532008	6.095372	9.009174
ln szmy	40	2.501	1.251817	0.1	4.98
ln <i>FDI</i>	40	5.2016	0.484391	3.291572	5.806917
ln <i>aGDP</i>	40	2.182406	0.4232442	1.235588	2.889816
ln <i>Tel</i>	40	7.717218	0.8171489	6.241053	9.443067
ln <i>Pg</i>	40	6.13999	0.9042193	4.077538	7.261927

From the above table, the average open-economic scale in the YRD region from 2013 to 2022 is 8.02, with a minimum of 6.10 and a maximum of 9.01, indicating a generally high level of open-economic development. However, the average score for digital trade development is 2.50, with a maximum of 4.98 and a minimum of 0.10, reflecting significant variation in digital trade development levels across different years and regions.

4.2 Regression Results and Analysis

4.2.1. Correlation Analysis Between Variables.

The results of the correlation analysis are presented in Table 6.

Table 6. Correlation Analysis of Variables.

	Ln y	Lnszmy	LnFDI	LnaGDP	LnTel	LnPg
ln y	1.000					
ln szmy	0.834***	1.000				
ln <i>FDI</i>	0.622***	0.537***	1.000			
ln <i>aGDP</i>	0.859***	0.651***	0.615***	1.000		
ln <i>Tel</i>	0.453***	0.679***	0.390***	0.456***	1.000	
ln <i>Pg</i>	0.921***	0.752***	0.453***	0.758***	0.339***	1.000

Note: *, **, *** represent significance at the 10%, 5%, and 1% levels, respectively.

The correlation analysis reveals a positive correlation between digital trade development level and the regional open-economic scale at the 1% significance level. Other control variables also show a positive correlation with the dependent variable. The results of the multicollinearity test for the variables show that the VIF values are all below 5, and the 1/VIF tolerance values are greater than 0.2. Strictly speaking, there is no multicollinearity. The results are shown in Table 7.

Table 7. Multicollinearity Test of Variables

Variable	VIF	1/VIF
$\ln szmy$	4.598	0.217485863
$\ln FDI$	1.756	0.569476082
$\ln aGDP$	3.250	0.307692308
$\ln Tel$	2.295	0.435729847
$\ln Pg$	4.123	0.242541838
Mean	3.2044	0.3545852

Note: *, **, *** represent significance at the 10%, 5%, and 1% levels, respectively.

4.2.2. Baseline Regression Results.

Using the data from 2013 to 2022 on digital trade development in the YRD region and the open-economic scale of the provinces and municipalities, we performed panel data regression using the OLS stepwise approach. The regression results are shown in Table 8.

Table 8. Empirical Results of the Impact of Digital Trade on Regional Open-Economic Development

	(1)	(2)	(3)	(4)	(5)
VARIABLES	$\ln y$	$\ln y$	$\ln y$	$\ln y$	$\ln y$
$\ln szmy$	0.635*** (0.068)	0.535*** (0.076)	0.354*** (0.062)	0.486*** (0.063)	0.261*** (0.061)
$\ln FDI$		0.482** (0.196)	0.095 (0.154)	0.112 (0.132)	0.211** (0.098)
$\ln aGDP$			1.186*** (0.196)	1.191*** (0.167)	0.680*** (0.152)
$\ln Tel$				-0.308*** (0.082)	-0.145** (0.066)
$\ln Pg$					0.452*** (0.080)
Constant	6.431*** (0.190)	4.175*** (0.936)	4.051*** (0.668)	5.999*** (0.770)	3.133*** (0.756)
Observations	40	40	40	40	40
R-squared	0.695	0.738	0.870	0.908	0.952

Note: *, **, *** represent significance at the 10%, 5%, and 1% levels, respectively.

Based on the regression results presented in the table above, the overall fit of the model is quite strong. In column (1), where the four control variables are not included, the regression model indicates that the level of digital trade development in the Yangtze River Delta (YRD) significantly promotes the expansion of the regional open economy scale. In column (2), the level of foreign direct investment (FDI) is added; in column (3), per capita GDP (aGDP) is incorporated; in column (4), the scale of regional telecommunication services (Tel) is included; and in column (5), the number of foreign investment projects (Pg) is considered. Based on these results, the following conclusions can be drawn:

First, with respect to the impact of the core variable on the scale of the regional open economy, it is evident that after gradually adding the four control variables, the coefficient for digital trade development in the YRD region remains positive in all five columns, and it passes the 1% significance level test. This suggests that improvements in digital trade development can significantly promote the expansion of the regional open economy scale.

Second, when the four control variables are included, the following conclusions can be made regarding the impact of digital trade development and the associated factors on the regional open economy scale:

1. The level of foreign direct investment (FDI) is significant at the 5% level, with a coefficient of 0.211. This indicates that for every 1% increase in foreign direct investment, the regional open economy scale increases by 0.211%. Specifically, during the sample period, controlling for other variables, a 1% increase in foreign investment in the YRD region results in a 0.211 percentage point increase in the open economy scale.
2. The coefficient for per capita GDP (aGDP) is positive and significant at the 1% level. A 1-unit increase in per capita GDP leads to a 0.680-unit increase in the regional open economy scale. This suggests that improvements in regional per capita GDP can effectively drive the development of import and export trade, thereby enhancing the regional open economy scale.
3. The scale of regional telecommunication services (Tel) is significant at the 1% level, but the coefficient is negative. This suggests that despite improvements in telecommunication technology and market size expansion, they have not promoted the growth of the regional open economy scale. This may be because limited data sources, it was not possible to distinguish between domestic and cross-border service. If conditions permit, the next research will be to conduct tests on domestic and cross-border business volumes separately. At the same time, considering that the development of communication services has led to more service-oriented trade, digital products have been launched online, promoting the development of cross-border e-commerce. These data have not been reflected in the positive impact of import and export trade through customs.
4. The number of foreign investment projects (Pg) is significant at the 1% level, with a coefficient of 3.133. This indicates that for every 1% increase in the number of foreign investment projects, the regional open economy scale increases by 0.452%. The presence of a complete domestic industrial chain, combined with foreign pro-

ject investments, means that most materials and services require domestic supply. This effectively promotes regional foreign trade development and, consequently, enhances the regional open economy scale.

4.3 Robustness Analysis of Model

This study conducts robustness tests using three methods. First, to address potential endogeneity issues in the relationship between digital trade and the scale of regional open economies, the study incorporates control variables step by step, which helps resolve some potential omitted variable problems. However, some unmeasurable factors may still exist. To address this, we first apply the second-order least squares method to test for endogeneity. Second, we perform a robustness check by replacing the core variables and modifying the way the regional digital trade development level is calculated. The specific calculation method is as follows: $Tszmy = \ln 10szmy$. Third, we apply data trimming. The robustness test results show that whether by reducing the sample period, replacing the core variables, or trimming the data at the 1% level, the level of digital trade development still passes the 1% significance level test, indicating a positive correlation between the two. This confirms that the main conclusions of the study are reliable.

4.4 Mechanism Tests: Mediation Effect Analysis

Building on the analysis of the impact mechanism of digital trade development on the regional open-economy scale in **Section 3.1**, this section uses a mediation effect model to empirically test **Hypotheses 1** and **2** and explore the mediation mechanism. The specific calculation models are as follows: Figure 2.

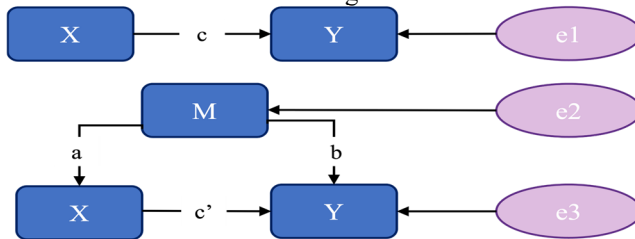


Fig. 2. Schematic Diagram of the Mediation Effect Model.

$$Y = cX + e_1 \quad (13)$$

$$M = aX + e_2 \quad (14)$$

$$Y = c'X + bM + e_3 \quad (15)$$

$$c = c' + ab \quad (16)$$

The coefficient c' represents the direct effect of the independent variable X on the dependent variable Y , after accounting for the influence of the mediator variable M .

Upon reviewing relevant studies, we found that most researchers use causal step-by-step testing methods for mediation testing, but this approach is cumbersome and difficult to yield clear and satisfactory results. Our study simulates that the Sobel test method has higher statistical power than sequential regression coefficient testing (Wen et al., 2004)^[16] as Sobel can detect more mediation effects. Therefore, this study adopts the method proposed by Wen et al. (2014)^[17] and applies the following steps for testing (Figure 3).

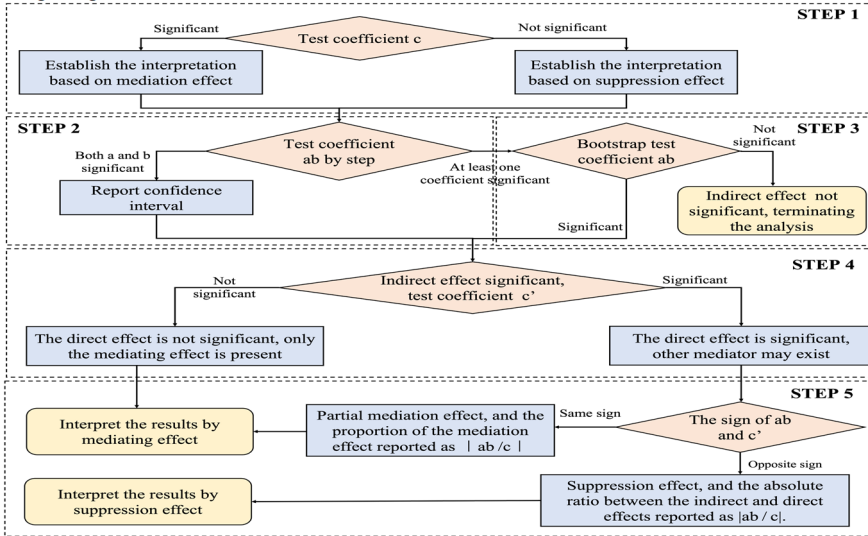


Fig. 3. Stepwise Mediation Effect Testing Flowchart.

4.4.1. Tertiary Industry Development as a Mediating Mechanism.

To further test the mediation effect of technological innovation and development between digital trade and open-economy scale, we construct the following mediation effect model:

$$Y_{kf} = \theta_0 + \theta_1 szmy_{it} + \theta_2 \ln Tel_{it} + \theta_3 \ln FDI_{it} + \theta_4 \ln aGDP_{it} + \theta_5 \ln Pg_{it} + \varepsilon_{it} \tag{17}$$

$$\text{Indscy}_{it} = \theta_0 + \theta_1 szmy_{it} + \theta_2 \ln Tel_{it} + \theta_3 \ln FDI_{it} + \theta_4 \ln aGDP_{it} + \theta_5 \ln Pg_{it} + \varepsilon_{it} \tag{18}$$

$$Y_{kf} = \theta_0 + \theta_1 szmy_{it} + \theta_6 \text{Indscy}_{it} + \theta_2 \ln Tel_{it} + \theta_3 \ln FDI_{it} + \theta_4 \ln aGDP_{it} + \theta_5 \ln Pg_{it} + \varepsilon_{it} \tag{19}$$

Here, we consider the third-sector output value of each province in the YRD as the mediating variable, with other variables serving as control variables. The third-sector output is log-transformed to represent the market scale level. The results of stepwise regression and the Sobel test are shown in Table 9 and Table 10.

The test results show that the coefficients of both the direct and total effect models of digital trade development are significantly positive, with a coefficient of 0.260866, and are significant at the 99% confidence level. This indicates that digital trade development has a significant positive impact on the expansion of the open-economy scale. After including the third-sector output index, the positive driving effect of digital trade development on the open-economy scale slightly decreases to 0.184024 but remains significant at the 99% confidence level, suggesting that there is a third-sector mediation effect. In other words, digital trade promotes the development of the third sector, which in turn drives the growth of the regional open economy. Likewise, the Sobel test shows that the p-value is less than 0.05, meaning the null hypothesis ($H_0: ab = 0$) is rejected and the mediation effect holds. The direct effect is 18.4%, the indirect effect is 7.68%, the total effect is 26.08%, and the proportion of the mediation effect is 29.5%. This conclusion validates Hypothesis 1.

Table 9. Mediation Mechanism Effect Analysis: Tertiary Industry Development.

	Coef.	Std Err	t	P> t	95% Conf. Interval	R-squared
$Y - X$	0.260866	0.06074	4.29	0.000	0.13742—0.38431	0.9527
$x_1 - X$	0.181818	0.05805	3.13	0.004	0.06384—0.29979	0.8392
$Y - x_1(X)$	0.422634	0.16663	2.54	0.016	0.08363—0.76164	0.9604
$Y - X_1(X)$	0.184024	0.64025	2.87	0.007	0.53765—0.31428	0.9604

Note: $Y - x_1(X)$ represents the effect of X_1 under the influence of X , while $Y - X_1(X)$ denotes the effect of X under the influence of x_1 . These effects are all calculated after incorporating four control variables.

Table 10. Sobel Test for Mediation Effect: Tertiary Industry.

	Coef.	Std Err	Z	P> Z
Sobel	0.07684238	0.03898451	1.971	0.04871243
Indirect effect	0.076842	0.038985	1.9711	0.048712
Direct effect	0.184024	0.064025	2.87426	0.00405
Total effect	0.260866	0.060743	4.29458	0.000018
Proportion of total effect that is mediated				0.29456641

4.4.2. Technological Innovation as a Mediating Mechanism.

To further test the mediation effect of technological innovation and development between digital trade and open-economy scale, we construct the following mediation effect model:

$$Y_{kf} = \theta_0 + \theta_1 szmy_{it} + \theta_2 \ln Tel_{it} + \theta_3 \ln FDI_{it} + \theta_4 \ln aGDP_{it} + \theta_5 \ln Pg_{it} + \varepsilon_{it} \quad (20)$$

$$\ln R\&D_{it} = \theta_0 + \theta_1 szmy_{it} + \theta_2 \ln Tel_{it} + \theta_3 \ln FDI_{it} + \theta_4 \ln aGDP_{it} + \theta_5 \ln Pg_{it} + \varepsilon_{it} \quad (21)$$

$$Y_{it} = \theta_0 + \theta_1 szmy_{it} + \theta_6 R \& D_{it} + \theta_2 \ln Tel_{it} + \theta_3 \ln FDI_{it} + \theta_4 \ln aGDP_{it} + \theta_5 \ln Pg_{it} + \varepsilon_{it} \tag{22}$$

We measure the level of technological innovation in the region by taking the logarithm of R&D expenditure in the provinces and municipalities of the YRD. The results show that the coefficients in both the total effect and direct effect models are significantly positive, with a coefficient of 0.260866, and are significant at the 99% confidence level. This indicates that digital trade development has a significant positive impact on the expansion of the open-economy scale. After including technological innovation as a mediating variable, the positive effect of digital trade development on the open-economy scale decreases to 0.167403 but remains significant at the 99% confidence level, indicating that technological innovation partially mediates the relationship between digital trade and the expansion of the open-economy scale. The Sobel test results show that the direct effect is 16.74%, the indirect effect is 9.35%, the total effect is 26.08%, and the proportion of technological innovation's mediation effect in the total effect is 35.83%. This confirms Hypothesis 2 Detailed results are presented in Table 11 and Table 12.

Table 11. Mediation Mechanism Effect Analysis: Technological Innovation.

	Coef.	Std Err	t	P> t	95% Conf. Interval	R-squared
$Y - X$	0.260866	0.06074	4.29	0.000	0.13742—0.38431	0.9527
$X_2 - X$	0.217568	0.06762	3.22	0.003	0.08016—0.35498	0.8491
$Y - x_2(X)$	0.429580	0.13735	3.13	0.004	0.15015—0.70901	0.9635
$Y - X(x_2)$	0.167403	0.61848	2.71	0.011	0.04157—0.29324	0.9635

Note: $Y - x_2(X)$ represents the effect of x_2 under the influence of X , while $Y - X(x_2)$ denotes the effect of X under the influence of x_2 . These effects are all calculated after incorporating four control variables.

Table 12. Sobel Test for Mediation Effect: Technological Innovation.

	Coef.	Std Err	Z	P> Z
Sobel	0.09345	0.04167	2.243	0.0249
Indirect effect	0.093463	0.41673	2.24277	0.024911
Direct effect	0.167403	0.061848	2.70668	0.006796
Total effect	0.260866	0.060743	4.29458	0.000018
Proportion of total effect that is mediated				0.35827827

Note: The p-value in the Sobel test is less than 0.05, which indicates the rejection of the null hypothesis ($H_0: ab = 0$), confirming the existence of the mediation effect. The direct effect is 16.74%, the indirect effect is 9.35%, the total effect is 26.08%, and the proportion of the mediation effect in the total effect is 35.83%.

4.4.3. Bootstrap Test of the Mediation Models.

Studies have shown that the Bootstrap method has higher statistical power compared to other mediation effect testing methods^[18]. To test the mediation effect more accu-

rately, we use the bootstrap method with 500 resamples, calculating the confidence intervals for the indirect effects and determining whether the confidence intervals contain 0. The results of the mediation effect, shown in the table below, indicate that the confidence intervals do not contain 0, confirming that the mediation effect is significant, as shown in Table 13. This further validates Hypotheses 1 and 2, confirming that digital trade development indeed promotes the expansion of the open-economy scale through these two mechanisms.

Table 13. Bootstrap Test Confidence Interval Results After 500 Resamples.

Dependent variables	Mediating variable	c	a	b	Confidence Interval	Conclusion
Y_{kf}	ln $dscy_{it}$	0.260866***	0.181818** *	0.422634***	0.0593	Partial Mediation Effect
		Std.err0.06074	0.05805	0.16663	—	
		Z 4.2946	3.1320	2.5364	0.3087	
	ln $R\&D_{it}$	0.260866***	0.217568** *	0.429580***	0.0364	Partial Mediation Effect
		Std.err0.06074	0.06762	0.13735	—	
		Z 4.2946	3.2178	3.1278	0.2984	

Note: calculated by stata

4.5 Summary of Empirical Findings

The empirical results are as follows:

1. By selecting four control variables, including foreign direct investment (FDI), per capita GDP (aGDP), regional telecommunication service scale (Tel), and the number of foreign investment projects (Pg), we confirm the significant impact of digital trade on the expansion of the open-economy scale in the YRD.
2. Given the potential bidirectional causality between digital trade and regional open-economy development, we performed an endogeneity test. We found that digital trade still positively promotes the expansion of the regional open-economy scale, albeit with a slightly reduced impact. Overall, improvements in digital trade development can enhance the open-economy scale, with a more significant effect at lower development levels.
3. After replacing the core variables and applying data trimming, the positive impact of digital trade on the YRD's open-economy scale is further confirmed.
4. Using the mediation effect model, we test the mechanisms through which digital trade drives the growth of the regional open-economy scale. We find that digital trade promotes the development of the third sector and technological innovation, which, in turn, drives the expansion of the open-economy scale.

5 Discussion

This study examines the impact of digital trade development on regional open-economic growth, using data from the Yangtze River Delta (YRD) region as a case study. The main conclusions are as follows:

1. Trends in Digital Trade Development (2013-2022):

Between 2013 and 2022, the digital trade development level in the YRD demonstrated an overall upward trend, with significant improvements in the comprehensive scores of digital trade development. This indicates that the region has actively leveraged information technology to enhance traditional trade, thereby driving digital trade growth. However, there are substantial disparities within the region. Jiangsu and Zhejiang are leading the way in digital trade development and open-economic scale, ranking in the top tier. In contrast, Anhui's digital trade development lags considerably behind the other provinces, with a notable deficiency in digital trade capabilities.

2. Empirical Analysis and Mechanism Testing:

In the empirical analysis and mechanism testing, the positive impact of digital trade development on regional open-economic growth remained significant as control variables were gradually added. The mediation effect model was employed to test the mechanisms underlying this relationship. The results validated both proposed hypotheses, showing that the development of the third sector and technological innovation serve as mediating factors. Specifically, digital trade development promotes the expansion of the open-economy scale by driving the growth of the third sector and fostering technological innovation, although the degree of influence varies across regions.

Based on the above findings, the following policy recommendations are made:

1. Digital Trade's Role in Open-Economic Development

Digital trade plays a crucial role in a region's external trade and significantly influences the development of its open economy^[19]. It has substantial growth potential and promising prospects. To expand regional digital trade openness, efforts should focus on increasing foreign investment access, enhancing investment fields and thresholds, promoting digital trade in external markets, and building robust digital platforms to support trade.

2. Balancing Domestic and International Markets

While expanding the regional digital trade market, it is important to safeguard local data security. The "domestic circulation as the primary focus, international circulation as a supplement, with a dual circulation approach" policy should be leveraged to enhance participation in international competition and cooperation. Emerging trade markets, such as BRICS countries and the Middle East, should be explored, while also competing with developed regions like the EU, the US, and Australia through e-commerce platforms.

3. Strengthening International Cooperation

Strengthening international exchanges and collaboration is essential for creating global platforms for digital trade. Encouraging enterprises to engage in international digital trade exchanges and cooperation will help boost global competitiveness and expand market reach.

4. Addressing Digital Trade Barriers

Digital trade barriers increase trade costs and hinder technological innovation, thereby complicating the export of manufacturing technologies^[20]. The government should work to optimize the business environment, reduce obstacles to digital trade development, and ensure smoother progress for the regional digital trade sector. Additionally, by leveraging the YRD's inherent regional advantages, establishing digital trade industrial clusters, and improving the regional digital trade development framework, high-quality economic growth can be fostered.

6 Conclusions

In conclusion, advancing digital trade development represents a significant opportunity for the Yangtze River Delta and other regions to enhance their open economies and achieve high-quality growth. The findings of this study suggest that policies promoting digital infrastructure, service sector digitalization, and technological innovation will not only directly boost trade but also indirectly strengthen the economy by modernizing industries and spurring innovation. By implementing the above policy recommendations, regions such as the YRD can better capitalize on the digital trade wave, balance openness with security, and lead the way in the new era of digitally enabled economic development.

Author Contributions

All authors contributed equally. All authors have read and agreed to the published version of the manuscript.

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