A Study on the Impact of Digital Economy on Implied Carbon Emissions from Trade in the Perspective of Global Value Chains

Yinghan Chen

School of Economics and Management, North China University of Technology, Beijing, China
Email: chenyinghan1997@163.com
Manuscript received June 21, 2023; revised July 30, 2023; accepted August 11, 2023; published March 20, 2024.

***Abstract*—At the intersection of the era of digital economy and the era of global value chains, digital technology and globalization are changing the world economy with explosive speed. This paper focuses on the impact of the development of digital economy on the trade-implied carbon emissions of developing countries under the perspective of global value chain, analyzes the endogenous determinants of trade-implied carbon emissions under the perspective of global value chain by constructing a theoretical model, and then analyzes the mechanism of the digital economy affecting the trade-implied carbon through the structural effect, technological effect, and the value chain upgrading effect under the perspective of global value chain. The two-way fixed effect model is used to test the impact of digital economy on trade-implied carbon under the perspective of global value chains and its mediating effect, and to analyze the heterogeneity. The results of the study show that: the development of digital economy can reduce the trade-implied carbon emissions of developing countries; in the context of economic globalization and the division of labor in the global value chain, the development of digital economy can reduce the trade-implied carbon emissions of developing countries by promoting the upgrading of the industrial structure, upgrading the level of technological development, and facilitating the upgrading of the economy's position in the global value chain. And the heterogeneity analysis shows that strengthening the construction of digital infrastructure, digital industry and the input of digital factors is conducive to better exerting the inhibiting effect of the development of digital economy on trade-implied carbon emissions. This has important policy implications for developing countries represented by China to promote the development of digital economy, low-carbon transformation and green transformation of export trade.**

***Keywords*—global value chains, digital economy, trade implied carbon, two-way fixed effects model**

I. Introduction

Global warming is becoming more and more serious, which has seriously threatened the future sustainable development of mankind. In this regard, the international community has formed a unanimous consensus and is taking a series of measures to cope with environmental degradation. In the foreseeable future, the focus of the international game will be on the allocation of carbon emission reduction responsibilities in the new round.

In the international context of global value chain division of labor, to achieve the goal of "double carbon", not only the carbon emission caused by domestic demand, but also the implicit carbon of trade to meet the demand of other countries needs to be given full attention. The division of labor in global value chains has become a new norm for countries to participate in international division of labor under economic globalization. The division of labor in global value chains has further strengthened the economic ties among countries, but also poses challenges for international carbon emission reduction. With the advantages of brand, technology and management, multinational enterprises in developed countries occupy a dominant and advantageous position in the division of labor in global value chains. While developing countries, with cheap labor and resources low-end embedded in the global value chain system, often undertake the transfer of pollution from developed countries. At the same time, the digital economy represented by "Internet+" and "Smart+" is booming. Digital technology with information and communication technology as the core is subtly changing the mode of multinational companies in international trade to develop business in overseas markets. Promoting the application of digital technology in traditional industries and realizing the networked, digitalized and intelligent development of each industry, so as to enhance its status and role in the division of labor in the global value chain, is of great significance to change the passive situation of developing countries and emerging economies receiving pollution transfer in the international division of labor. Based on this, this paper tries to explore the impact of the development of digital economy on the implied carbon of trade and the path of action from the perspective of global value chain, which has strong theoretical and practical significance.

In recent years, scholars at home and abroad have analyzed the environmental effects of digital economy development from different perspectives, especially the relationship between digital economy development and carbon emissions, but the existing studies have not yet formed a unified definitive conclusion.

Most scholars believe that the development of the digital economy improves the environmental situation and provides an impetus for emission reduction (Watanabe *et al.*, 2018; Zhang *et al.*, 2022; Wang *et al.*, 2022; Zhang *et al.*, 2022). First, at the macro governance level, with the addition of digital technologies, the government can better understand energy market trends and price movement trends and control total energy supply through pricing and cross-subsidies. Secondly, from the meso-industrial structure, the penetration of digital technology comprehensively promotes the optimization and upgrading of industrial structure, which enables the transfer of production factors from inefficient sectors to high-efficiency sectors and improves resource allocation efficiency, ultimately promoting the improvement of energy efficiency and the reduction of carbon emissions

doi: 10.18178/ijtef.2024.15.1.766

(Suke and Zhou, 2021); finally, from the micro-enterprise level, the application of digital technology can not only optimize the enterprise carbon emission The application of digital technology can not only optimize the end-of-pipe management technology of enterprises' carbon emissions, but also achieve real-time collection, monitoring, transmission and analysis of energy data by accurately grasping energy flow data and guiding energy factors to achieve high-efficiency allocation (Wu and Gao 2020). In addition, from the perspective of energy saving, the digital economy breaks regional boundaries and breaks through time constraints, accelerates the flow and production of factors, and saves energy consumption in production and life due to space and time factors in production life, thus reducing the rate of energy loss and promoting the improvement of energy use efficiency, thus curbing carbon emissions. However, there are some studies with different views. Some scholars (Salahuddin *et al.*, 2015; Avom *et al.*, 2020) argue that the development of digital technologies will lead to high electricity consumption and energy consumption, which will increase carbon emissions. Some other studies have found that the digital economy has a nonlinear effect on spatial carbon emissions, with an inverted U-shaped local carbon reduction effect that first promotes growth and then suppresses it, and an inverted U-shaped spatial spillover reduction effect that first suppresses and then promotes growth under economic agglomeration (Li & Wang, 2022). And only a few scholars have explored the relationship between the digital economy and trade implied carbon, and the related research is still in its initial stage. And the existing studies lack the analysis of the environmental effects of the digital economy in the perspective of global value chains. This paper incorporates global value chains into the analysis framework of the environmental effects of digital economy, and integrates digital economy, trade implied carbon and global value chains into a unified research and analysis framework, which makes up for the shortage of existing research and has strong theoretical and practical significance.

II. Theoretical Analysis and Research Hypotheses

A. Analysis of Endogenous Determinants of Implied Carbon Emissions from Trade in the Perspective of Global Value Chains

Grossman & Krueger (1991) first proposed the "environmental triple effect" of free trade on the environment, i.e., scale effect, structural effect and technology effect, which provided a basic analytical framework for discussing the environmental effects of trade. Subsequently, different scholars have further extended the "environmental triple effect", and the analytical framework of "environmental triple effect" has been cited in the research of related fields. In this paper, based on the framework of trade and environment analysis constructed by previous authors, we construct a theoretical model to analyze the endogenous determinants of trade implied carbon emissions from the perspective of global value chain division of labor, so as to analyze the endogenous determinants of trade implied carbon and the impact of digital economy on trade implied carbon from the perspective of global value chain.

Suppose an open economy satisfies the following conditions:

1) Only two final products *X* and *Y* are produced, where *X* is a polluting good that produces carbon emissions and Y is a clean good that does not produce any carbon emissions, and only two factors of production, capital *K* and labor *L*, are available;
2) The production of product *X* undergoes global value chain division of labor, and its production process is at stage δ of the global value chain, and a larger δ indicates a higher position in the value chain at that stage;
3) Only the implied carbon emission effect is considered and other environmental effects are ignored;
4) The market is perfectly competitive.

Assuming that the potential output of product $X = f(K_X, L_X)$, where K_X , L_X denotes the capital and labor inputs required to produce product X, respectively, in order to reduce the cost brought about by the levy of a carbon tax, the enterprise will put part of its revenue into the emission reduction work. Assuming that a proportion t (0 < t < 1) of the potential output is invested in carbon abatement, then the actual output of product *X* and the carbon emissions C it generates are:

$$X = (1-t)f(K_X, L_X) \tag{1}$$

$$C = \varphi(t) f(K_X, L_X) \tag{2}$$

Assuming that a μ fraction of product X is exported around the world, the implied carbon emissions of the economy's exports as Eq. (3) shown:

$$C_{ex} = \mu\varphi(t) f(K_X, L_X) \tag{3}$$

$\varphi(t)$ is a decreasing function about t, indicating that the level of carbon emissions gradually decreases as the cost invested into energy-saving and emission-reducing technologies increases. Here the specific form of $\varphi(t)$ is set as follows:

$$\varphi(t) = \frac{1}{T}(1-t)^{1/\alpha}, \quad 0 < \alpha < 1 \tag{4}$$

where T is the production technology level, thus:

$$C = \frac{1}{T}(1-t)^{1/\alpha} f(K_X, L_X) \tag{5}$$

$$C_{ex} = \mu\frac{1}{T}(1-t)^{1/\alpha} f(K_X, L_X) \tag{6}$$

Then the influence of global value chain factors is introduced. In the world market, a country's position in the global value chain determines the form of its participation in the international division of labor, which in turn has an impact on the country's carbon emissions. If a country is at the higher end of the global value chain, it produces products with high added value and low pollution, consumes less traditional resources, and has higher-end human resources to promote more efficient use of capital and natural resources through advanced management experience and technology. If it is at the low end of the global value chain, it produces products with low added value and higher pollution. The carbon emission and export implied carbon emission functions of sector X after participating in the international division of labor are:

$$C=\frac{1}{T}(1-t)^{1/\alpha}f(K_X,L_X)w(\delta) \quad (7)$$

$$C_{ex}=\mu\frac{1}{T}(1-t)^{1/\alpha}f(K_X,L_X)w(\delta) \quad (8)$$

$w(\delta)$ denotes the impact function of carbon emission effect of global value chain.

And the actual production of product X can be expressed as:

$$X=(1-t)f(K_X,L_X)=(TC)^{\alpha}f(K_X,L_X)^{1-\alpha}w(\delta)^{-\alpha} \quad (9)$$

Assume that the country imposes the carbon tax $\tau=\gamma TC$, and TC is the effective carbon emissions after considering the level of technology, γ is the carbon tax rate. Let the potential cost per unit of producing X product be $C^f(w,r)$, then the optimal decision at this point is to seek the optimal potential output $f(K_X,L_X)$ and carbon emission C, so that the production cost and environmental cost are minimized, i.e:

$$\min\left\{\gamma TC+C^f(w,r)\times f(K_X,L_X)\right\} \quad (10)$$

$$s.t.(TC)^{\alpha}f(K_X,L_X)\times w(\delta)^{-\alpha}=\lambda \quad (11)$$

From the Lagrange multiplier method, we can find that:

$$\frac{C^f(w,r)}{\gamma}=\frac{(1-\alpha)\ TC}{\alpha f(K_X,L_X)} \quad (12)$$

In a perfectly competitive market, firms make zero profit on production, and thus:

$$XP_X=C^f(w,r)f(K_X,L_X)+\gamma TC \quad (13)$$

Combining the two equations above yields:

Actual production of product $X=\frac{\gamma TC}{\alpha p_X}$ (14)

Thus, the carbon emission per unit of producing X product

$$\frac{C}{X}=\frac{\alpha p_X}{\gamma T} \quad (15)$$

Also by

$$C_{ex}=\mu\frac{1}{T}(1-t)^{1/\alpha}f(K_X,L_X)w(\delta) \quad (16)$$

Replace the above equation with

$$C_{ex}=\mu\frac{1}{T}(1-t)^{1/\alpha}f(K_X,L_X)w(\delta)=\varphi(t)\times\mu S\times G_X\times w(\delta) \quad (17)$$

In which,

$$S=f(K_X,L_X)+f(K_Y,L_Y) \quad (18)$$

$$G_X=f(K_X,L_X)/f(K_X,L_X)+f(K_Y,L_Y) \quad (19)$$

Then,

$$C_{ex}=\frac{\alpha p_X}{\gamma T}\times\mu S\times G_X\times w(\delta) \quad (20)$$

Taking the logarithm of both sides of the equation, we get:

$$\ln C=\ln(\alpha p_X)+\ln(\mu S)+\ln(G_X)+\ln w(\delta)-\ln\gamma-\ln T \quad (21)$$

where $\ln(\alpha p_X)$ is a constant, μS denotes the export scale of the country, G_X is the industrial structure of the country, $w(\delta)$ denotes the influence function of the carbon emission effect of the global value chain, γ is the carbon tax rate, and T is the level of production technology. The formula shows that the implied carbon of export trade is determined by the export scale, industrial structure, global value chain status, technology level and carbon tax. Thus, we further analyze the impact mechanism of digital economy on trade implied carbon from three aspects: structural effect, technological effect and value chain upgrading effect.

B. Analysis of the Mechanism

First, the structural effect. The digital economy has the advantages of low transaction costs, fast dissemination, efficient processing of information, and the realization of rapid matching between supply and demand, which can promote the optimization and upgrading of industrial structure. The development process of digital economy changes the types and proportions of input factors in production through its characteristics of permeability, substitution and synergy, reshapes the production relationship in the traditional economy and innovates the original production model. Digital transformation can promote production organization optimization and production process reengineering, improve the efficiency of inter-system collaboration, and achieve advanced industrial structure and transformation and upgrading (Wang & Yuan, 2022), thus making the industrial structure change from resource- and human-intensive to capital-intensive, while the latter requires less energy and can significantly reduce carbon emissions. Therefore, the digital economy can reduce the implied carbon emissions of trade by promoting the transformation and upgrading of industrial structure.

Second, the technology effect. On the one hand, from the internal level, the development of the digital economy can produce technological spillover effects, improve the operational efficiency and innovation efficiency of enterprises, and promote the improvement of technological innovation capacity in various industries. The application of big data, artificial intelligence and robotics is accelerating the change of production and operation methods in various industries; on the other hand, from the external level, the development of digital economy is conducive to broadening financing channels and alleviating financing constraints, which is one of the main factors hindering technological innovation of enterprises; In addition, the development of digital economy helps break down the information barrier between buyers and sellers, providing consumers with a wide space of choice (Hu & She, 2022), thus increasing consumers' demand for market goods and services, which undoubtedly accelerates market competition and thus enhances the driving force of technological innovation in various industries. The development of technological innovation, especially the development of clean technology, is undoubtedly conducive to energy conservation and the reduction of carbon emission levels, so the development of the digital economy can reduce trade implied carbon by promoting technological progress.

Third, the value chain climbing effect. On the one hand, the digital economy has reduced the trade costs of intermediate and final goods in international trade, promoting the increase of trade value-added in various industries and the rise of the global value chain division of labor (Qi & Ren, 2021). The development of digital economy has broken the limitation of spatial geographical location for international trade, and in the era of digital economy, the transportation cost of digital products and services tends to zero, while artificial intelligence promotes the improvement of storage and logistics efficiency, thus reducing the transportation cost; big data network and instant information sharing effectively reduce the information asymmetry of different trade links in the value chain and compress the information cost; digital network platform services improves the efficiency of production convergence and cooperation between enterprises in each node of the value chain, and reduces market costs such as marketing costs and coordination and management costs. On the other hand, new development dynamics such as big data network, artificial intelligence and Internet of everything have greatly changed the traditional business model. With the refinement and deepening of GVC division of labor, more and more multinational enterprises are integrated into the global production network. The application of network digital platform helps to realize data and information sharing, R&D collaboration and decision synchronization among enterprises in different countries and different value chain links, and enhance the efficiency of global collaborative division of labor, thus promoting the improvement of production and operation efficiency in various industries. And as the status of global value chains climbs, developing economies shift from passively undertaking highly polluting labor-intensive and resource-intensive industries to industries with high added value and cleaner and more efficient production, thus reducing the implied carbon emissions of trade. Therefore, the digital economy can reduce trade implied carbon emissions through the value chain climbing effect.

In summary, the following hypotheses are proposed in this paper:

Hypothesis 1: The development of the digital economy can reduce trade-implied carbon emissions in developing countries.

Hypothesis 2: The development of the digital economy can reduce the trade-implied carbon emissions of developing countries through structural effects.

Hypothesis 3: The development of the digital economy can reduce the trade-implied carbon emissions of developing countries through technological effects.

Hypothesis 4: The development of the digital economy can reduce the trade-implied carbon emissions of developing countries through the value chain upgrading effect.

III. Model Setting, Variables Selection and Data Sources

A. Model Setting

1) Benchmark model

Here, to test the impact of digital economy on trade implied carbon, the benchmark model is constructed as follows:

$$ECI_{it} = \alpha_0 + \alpha_1 Digital_{it} + \alpha_2 X_{it} + \varphi_i + \varphi_t + \varepsilon_{it} \quad (22)$$

where i and t denote country and time, *ECI* represents the carbon intensity of export trade, and *Digital* represents the level of development of the digital economy. *X* denotes the control variable, φ_i, φ_t and ε_{it} denote the country and year fixed effects and random error terms, respectively.

2) Mediating effects model

Combined with the above theoretical analysis, the development of digital economy can reduce the trade-implied carbon emissions of developing countries through the structural effect, technological effect, and value chain upgrading effect. In order to verify whether this mechanism of action is valid, this paper further constructs a mediation effect model to verify it.

$$Z_{it} = \beta_0 + \beta_1 Digital_{it} + \beta_2 X_{it} + \varphi_i + \varphi_t + \varepsilon_{it} \quad (23)$$

$$ECI_{it} = \lambda_0 + \lambda_1 Digital_{it} + \lambda_2 Z_{it} + \lambda_3 X_{it} + \varphi_i + \varphi_t + \varepsilon_{it} \quad (24)$$

where *Z* denotes the mediating variables, including industrial structure, technology level and global value chain status index, and the meanings of other variables are consistent with the benchmark model.

B. Variables Selection

1) Explained variables

Trade-implied carbon emissions are divided into export-implied carbon emissions and import-implied carbon emissions. Among them, export-implied carbon emissions refer to the carbon emissions generated by the domestic production of products that are exported and consumed abroad, while import-implied carbon emissions refer to the carbon emissions generated by the domestic production of products that are imported and consumed domestically. Exploring the export-implied carbon emissions is more important for a country's green and low-carbon development. Here, we construct a unit-value export-implied carbon emission index to measure the emission intensity of export-implied carbon:

$$ECI_i = \frac{EXC_i}{EX_i} \quad (25)$$

Among them, ECI_i represents the implied carbon intensity of country i's exports, EXC_i represents the carbon emissions of country i's exports, and EX_i represents the total export volume of country i.

2) Explanatory variables

In this paper, we refer to the measurement method of the World Economic Forum on Network Readiness Index, and measure the level of digital economy development of economies by constructing the Digital Economy Development Index of economies (*Digital*), and the specific indicator measurement system is shown in the table, and all three-level indicators are standardized.

Table 1. Indicator measurement system of digital economy development level of economies

First Level Indicators	Second level indicators and their weights in relation to First level indicators		Third level indicators and their weights in relation to second level indicators		Data sources
Digital economy	Digital Infrastructure	1/4	Secure Web Server Coverage	1	World Development Indicators Database (WDI)
	Digital Users	1/4	Fixed broadband subscription rate	1/3	
			Percentage of individuals using the Internet	1/3	
			Mobile Cellular subscription rate	1/3	
	Digital Industries	1/4	ICT goods exports as a share of goods exports	1/4	
			ICT service exports as a share of service exports	1/4	
			Digital manufacturing value added as a share of GDP	1/4	Organization for Economic Cooperation and Development (OECD)world input-output tables
			Digital services value added as a share of GDP	1/4	
	Digital Application	1/4	Digital manufacturing inputs as a share of total inputs	1/2	
			Share of digital services inputs in total inputs	1/2	

3) Intermediate variables

a) Global value chain position index GVC_pos

Drawing on Koopman to construct an index to measure a country's position in the GVC division of labor as follows:

$$GVC\_pos_i = \ln(1+\frac{IV_i}{E_i}) - \ln(1+\frac{FV_i}{E_i}) \tag{26}$$

GVC_pos_i is the index of country i's GVC position, and a larger value of GVC_pos_i indicates a higher position of country i in the division of labor in the GVC (i.e., closer to the upstream link). where IV_i and FV_i denote country i's indirect value added exports and foreign value added included in exports, respectively, and E_i is country i's total exports. $\frac{IV_i}{E_i}$ is also known as the GVC Forward Participation Rate Index, it indicates the extent to which country r's intermediate goods are used by importing countries to produce final goods and exported to third countries, with a higher index indicating that country i is further up the value chain in the global value chain. And $\frac{FV_i}{E_i}$ is also known as the GVC backward participation index, a higher index indicates that country r is further down the value chain in the global value chain.

b) Industry structure Ins

This paper adopts the ratio of the added value of the tertiary industry to that of the secondary industry to measure the degree of advanced industrial structure. It reflects the process that the proportion of the three industries is rising along the order of primary, secondary and tertiary industries and the industrial structure is being optimized with the economic growth.

c) Technology level Tech

This paper uses the total factor productivity of individual economies to measure the level of technological development of a country.

4) Control variables

Five control variables were selected for this paper: export size (*Export*): measured by the country's total exports in each year. the level of economic development (*Rgdp*): measured by the country's GDP per capita; Foreign direct investment (*Fdi*):measured by the net foreign direct investment flows of the country as a share of GDP; the level of urbanization (*Urbanization*): measured by the ratio of the urban population to the total population of each country; and the level of consumption (*Cpi*): measured by the consumer price index of the country.

C. Data Sources

The empirical data in this paper cover 24 developing countries worldwide, spanning the period 2008-2018, with the data required to measure the explanatory variables sourced from the OECD's Implicit Trade in Carbon ($TECO_2$) database, the data required to measure the core explanatory variables sourced from the World Development Indicators database and the OECD World Input-Output Database, and the data required for the mediating and control variables sourced mainly from the OECD s Value Added Trade Database, the World Development Indicators Database, the United Nations Commodity Trade Database, Payne World Tables Version 10.0, and Big Data for International Open Source Research.

24 Economies including: Argentina, Brazil, Bulgaria, Russia, Philippines, Kazakhstan, Cambodia, Laos, Romania, Malaysia, Peru, Myanmar, Morocco, South Africa, Saudi Arabia, Thailand, Turkey, Brunei, India, Indonesia, Viet Nam, Chile, China, Mexico.

IV. Basic Empirical Results and Analysis

A. Benchmark Regression Results

Columns (1) and (2) of Table II show the results of the full-sample regressions without the control variables as well as after the control variables are added, respectively. And the coefficients on the level of development of the digital economy are always significantly negative, indicating that the development of the digital economy in developing countries is conducive to the reduction of the carbon intensity of the export trade, making exports "cleaner", and verifying Hypothesis 1. For the control variables. For the control variables, the coefficient of total exports is significantly negative, indicating that with the development of economies of scale and the reduction of trade costs, the implied carbon emissions from exports are reduced; the coefficient of the level of economic development is significantly negative, indicating that with the improvement of the level of economic development of the economies, the value of carbon intensity of export trade decreases, and the exports are "cleaner". This is mainly because a higher level of economic development increases people's demand for a high-quality environment, and consumers are more inclined to buy green and low-carbon products and services, which promotes the green and low-carbon transformation of all industries, thus contributing to the reduction of the implied carbon intensity of exports. The coefficient of urbanization is significantly positive, the reason for this is that most developing countries are still in the medium-low level stage of urbanization, and the awareness of low-carbon environmental protection of the new urban population is still relatively weak (Wang & Cheng, 2020), which, to a certain extent, contributes to the increase of trade-implied carbon. However, the coefficients of the consumer price index and foreign direct investment are not significant, indicating that the impact of the two on trade-implied carbon is not obvious.

Table 2. Benchmark regression results

Variable name	(1)	(2)
Digital	−0.4493** (0.098)	−0.2133*** (0.0650)
Export		−1.13e–07*** (1.44e–08)
Rgdp		−8.68e–07*** (3.24e–07)
Fdi		0.0006 (0.0003)
Urbanization		8.02e–06*** (1.63e.06)
Cpi		7.93e.06 (4.67e.05)
cons	0.1367*** (0.0185)	−3.8498*** (−3.7075)
country, year fixed effects	Yes	Yes
sample size	264	264
Adjusted R^2	0.7994	0.9526

Note: $^*p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$, robust standard errors in parentheses (the same as below)

B. Mechanism Testing

The benchmark regression verifies that the digital economy can reduce the trade-implied carbon, in order to deeply understand the intrinsic relationship between the two, this paper applies the method of stepwise regression to test the possible existence of the role of the mechanism, i.e., whether the development of the digital economy can reduce the terms of trade of pollution through the structural effect, the technological effect, and the effect of the climb of the value chain, and the test results are shown in Table 3.

Table 3. Mediation effect test results

Variable name	Structural effect		Technology effect		Value chain upgrading effect	
	(1)	(2)	(3)	(4)	(5)	(6)
	Ins	ECI	Tech	ECI	GVC_pos	ECI
Digital	1.6460*** (0.6124)	−0.2134*** (0.6525)	0.9952*** (0.2140)	−0.200*** (0.0656)	0.36341** (0.1248)	−0.1999*** (0.0663)
Ins		−0.0867*** (0.0039)				
Tech				−0.0515*** (0.0196)		
GVC_pos						−0.0037*** (0.0013)
control variables	Yes	Yes	Yes	Yes	Yes	Yes
Economy, year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
sample size	264	264	264	264	264	264
Adjusted R^2	0.8617	0.8057	0.9620	0.9628	0.8506	0.9552

First, for the structural effect, the result in column (1) shows that the coefficient of the level of development of digital economy is significantly positive, indicating that the development of digital economy in developing countries can significantly promote the optimization and upgrading of the industrial structure, which can make the industrial structure change from resource- and manpower-intensive to capital-intensive. Column (2) shows that the coefficient of industrial structure is significantly negative, indicating that the optimization and upgrading of industrial structure can reduce the carbon intensity of export trade. The regression results in Column (1) and Column (2) verify Hypothesis 2, that is, the digital economy can reduce the implied carbon emissions of trade by promoting the transformation and upgrading of industrial structure.

Second, for the technology effect, the results in column (3) show that the coefficient of the level of digital economy development is significantly positive, indicating that the development of digital economy in developing countries can significantly contribute to the level of technology development. Column (4) shows that the coefficient of the level of technology is significantly negative, indicating that upgrading the level of technology is an effective means to reduce the carbon intensity of export trade. The improvement of technology level is the fundamental driving force for the transformation of the economic model from high energy consumption and high emission to green and low-carbon economy, which can reduce energy consumption and improve the efficiency of energy utilization, thus reducing the implied carbon intensity of exports. The regression results in Column (3) and Column (4) validate Hypothesis 3, that is, the economic development of developing countries' figures can reduce the export-implied carbon intensity through the technology effect.

Finally, for the value chain climbing effect, the results in column (5) show that the coefficient of digital transformation is significantly positive, indicating that the development of digital economy in developing countries can contribute to the climbing of their value chain position. Column (6) shows that the coefficient of the global value chain status index is significantly negative, indicating that the climbing of developing countries' global value chain status can reduce trade-implied carbon emissions. The rise of developing countries in the index of global value chain status implies the change of status in the international division of labor system, which is conducive to changing the passive situation of accepting the transfer of pollution in the international division of labor, thus reducing the implicit carbon intensity of exports. The regression results in columns (5) and (6) verify hypothesis 4, that is, the development of the digital economy in developing countries can reduce the implicit carbon intensity of exports through the value chain upgrading effect.

C. Endogeneity Treatment and Robustness Tests

Considering the endogeneity problem caused by two-way causality, this paper applies two-stage least squares regression. In the selection of instrumental variables, this paper draws on the ideas of Huang (2019) and Zhao 2020, etc. to use the interaction term between the fixed-line penetration rate of each country in 1984 and the digitization investment in the previous year as an instrumental variable for the level of development of the country's digital economy. Column (1) in the table shows the results of the two-stage least squares regression. The sign and significance of the coefficients of the core explanatory variables are consistent with those of the benchmark regression results, which suggests that the study's conclusions are still robust after taking into account possible endogeneity.

In order to test the robustness of the above regression results, firstly, the model estimation is carried out by replacing the measures of the explained variables and introducing the lag 1 period of the explanatory variables. (In this paper, we refer to Huang (2017), who re-measured the export-implied carbon intensity of developing countries.) Considering the possible two-way interaction between the development of the digital economy and the trade-implied carbon emissions, this paper introduces a first-order lag term of the explanatory variables and conducts a re-regression. Secondly, in order to circumvent the interference of extreme values on the test results, the extreme values of 5% before and after all variables are shrink-tailed, and the regression results are shown in column (4). According to the test results, the regression coefficients of all the explanatory variables are significantly negative, which effectively verifies the inhibiting effect of the development of digital economy on trade-implied carbon emissions.

Table 4. Endogeneity treatment and robustness test results

Variable name	Endogeneity	Replacement of explained variables	Introducing first-order lag terms for explanatory variables	Extreme value treatment
	(1)	(2)	(3)	(4)
Digital	−0.3247*** (0.0541)	−0.8123*** (0.1957)	−0.3249*** (0.0536)	−0.6817*** (0.1589)
control variables	Yes	Yes	Yes	Yes
country, year fixed effects	Yes	Yes	Yes	Yes
Anderson can. Corr. LM statistic	896.304***			
Cragg-Donnald Wald F statistic	4750 {13.72}			
Hauaman test P-value	0.1024			
sample size	264	264	264	264
Adjusted R^2	0.8954	0.7459	0.9610	0.9332

D. Heterogeneity Analysis Based on Dimensions of Digital Economic Development and Types of Digital Inputs

In order to explore the differences in the impact of different dimensions of the development of the digital economy of a country on trade-implied carbon, it is of great significance to optimize the development strategy of the digital economy in order to give full play to its low-carbon effect. On the one hand, as far as the development of digital economy is concerned, there may be differences in the impact of changes in the level of development of digital economy in different areas on trade-implied carbon, so this paper examines the impact of the development of digital economy on trade-implied carbon from the different levels of development of the three dimensions of digital infrastructure, digital manufacturing inputs, and digital service inputs, respectively, based on the average value of development level of the three dimensions of the digital economy of the country in the period from 2008 to 2018, and divides the 24 developing economies into three categories. The specific method is to classify 24 developing economies into high digital infrastructure sophistication economies and medium-low digital economy infrastructure sophistication economies, high digital manufacturing input economies and medium-low digital manufacturing input economies, and high digital service input economies and medium-low digital service input economies based on the mean value of the development level of the countries in the three dimensions of the digital economy from 2008 to 2018, and regress them separately, and the estimation results are shown in columns (1) to (6) of the table. The absolute value of the coefficient on the level of digital economy development in column (1) is significantly larger than that in column (2), indicating that the development of digital economy has a more significant effect on the reduction of trade-implied carbon in countries with better digital infrastructure. The absolute value of the coefficient of the level of development of digital economy in column (3) is slightly larger than that in column (4), which indicates that the development of digital economy has a more significant effect on the reduction of trade-implied carbon in countries with more investment in digital manufacturing. The absolute value of the coefficient of the level of development of digital economy in column (5) is significantly larger than that in column (6), indicating that the development of digital economy has a more significant effect on the reduction of trade-implied carbon in countries with more inputs of digital services. The difference between the results in Column (5) and Column (6) is larger than that in Column (3) and Column (4), which indicates that the impact of different levels of digital service inputs on the suppression of trade-implied carbon by the digital economy is larger than that of different levels of digital manufacturing inputs. This is due to the fact that digital manufacturing inputs are more energy-intensive than digital services inputs, whereas the digital services sector is “cleaner”, and thus higher inputs of digital services are more likely to contribute to the carbon-reducing effects of digital economy development.

Table 5. Heterogeneity test results

Variable name	Digital Infrastructure		Digital Manufacturing Inputs		Digital services inputs	
	Economies with high levels of digital infrastructure sophistication	Economies with Low to medium digital infrastructure sophistication	High Digital manufacturing input economies	Low to medium digital manufacturing input economies	High digital services input economies	Low to medium digital services economies
	(1)	(2)	(3)	(4)	(5)	(6)
Digital	−0.5613*** (0.1044)	−0.3306*** (0.0612)	−0.5189*** (0.0729)	−0.3637*** (0.0674)	0.5017*** (0.0981)	0.2099*** (0.0225)
control variables	Yes	Yes	Yes	Yes	Yes	Yes
country, year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
sample size	154	110	176	88	143	121
Adjusted R^2	0.9314	0.9597	0.9332	0.9467	0.9526	0.9129

V. Conclusions and Insights

Based on the data of 24 developing countries from 2008 to 2018, this paper explores the impact of the development of digital economy on trade-implied carbon and its mechanism of action under the perspective of global value chains. The research conclusions of this paper are as follows:

(1) The development of digital economy in developing countries can reduce trade-implied carbon emissions. (2) The development of digital economy in developing countries can reduce trade-implied carbon emissions through structural effects, technological effects, and value chain upgrading effects. (3) Heterogeneity tests suggest that the dampening effect of the development of the digital economy on trade-implied carbon emissions is better realized by strengthening the economy’s digital economy infrastructure and increasing investment in the digital sector, especially in digital services.

These findings have important policy implications for developing countries represented by China to promote the development of digital economy, low-carbon transformation and green transformation of export trade: (1) The core elements of promoting the development of digital economy should be accurately grasped, and the investment in digital manufacturing and digital services should be increased, and at the same time, efforts should be made to strengthen the construction of digital infrastructure, so as to create a favorable policy environment for the development of digital economy. (2) The development of the digital economy should empower the enhancement of technological innovation capacity, give full play to the development of digital technology and the application of digital equipment brought about by the technological spillover effect and penetration effect, and promote the enhancement of the technological innovation capacity of various industries and the development of green technology, so as to promote the green and low-carbon transformation of various industries. (3) Promote the overall improvement of the level of development of the digital economy by consolidating the construction of digital infrastructure, promoting the development of digital industries and the transformation of digital users, so as to take this as a focus point to promote the optimization and upgrading of the industrial structure and the upgrading of the status of the global value chain, so as to change the unfavorable situation of the developing economies' own passive acceptance of pollution in the international division of labor, and to promote the green and low-carbon transformation of export trade.

Conflict of Interest

The author declares no conflict of interest.

References

Avom, D., Nkengfack, H., Fotio, H.K., Totouom, A. 2020. ICT and environmental quality in Sub-Saharan Africa: Effects and transmission channels. ***Technological Forecasting and Social Change***. 155, 120028.

Grossman, G. M., Kruger, A. B. 1991. ***Environmental Impacts of the North American Free Trade Agreement***. NBER Working Paper.

Hu, H. Y., She, Q. Z. 2022. Can the digital transformation of manufacturing reduce the implied carbon intensity of exports. ***International Trade Issues***, (07): 36-52.

Huang, L. Y., Xie, H. Q., Liu, D. D. 2017. Technological progress path selection and implied carbon emission intensity of China's manufacturing exports. ***China Population-Resources and Environment***, 27(10): 94-102.

Huang, Q. H., Yu, Y. Z., Zhang, S. L. 2019. Internet development and manufacturing productivity improvement: Internal mechanism and Chinese experience. ***China Industrial Economy***, (08): 5-23.2019.08.00

Zhang, J. N., Lyu, Y. W., Li, Y. T., Geng, Y. 2022. Digital economy: An innovation driving factor for low-carbon development. ***Environmental Impact Assessment Review***. 96, 106821.

Jun, W., Xi, L., Jie, Z. 2022. Does the digital economy contribute to carbon emissions reduction? A city-level spatial analysis in China. ***Chinese Journal of Population, Resources and Environment***. 20: 105–114.

Koopman, R., Powers, W., Wang, Z., Wei, S. J. 2010. Give credit where credit is due: Tracing value added in global production chains. ***NBER Working Paper***, no. 16426.

Qi, J. Y., Ren, Y. D. 2021. The impact of digital economy penetration on the position of global value chain division of labor-a cross-country empirical study based on industry heterogeneity. ***International Trade Issues***, (09): 105-121. 2021.09.007.

Salahuddin, M., Alam, K. 2015. Internet usage, electricity consumption and economic growth in Australia: A time series evidence. ***Telematics and Informatics***. 32, 862–878.

Su, K., Zhou, C. 2021. Human capital, science and technology innovation and green total factor productivity-an analysis based on data from cities in the Yangtze River Economic Belt. ***Economic Issues***, (05):71-79, 2021.05.011.

Wang, F., Yuan, C. L., Ma, N. 2022. The impact of digital economy development on industrial structure and industrial efficiency: empirical evidence from provincial level. ***China Science and Technology Forum***, (12): 117-127.2022.12.012.

Wang, X. J., Cheng, Y. 2020. Research on the impact mechanism of urbanization on carbon emission efficiency-an empirical analysis based on global panel data of 118 countries. ***World Geography Research***, 29(03): 503-511.

Watanabe, C., Naveed, K., Tou, Y., Neittaanmaki, P. 2018. Measuring GDP in the digital economy: Increasing dependence on uncaptured GDP. ***Technological Forecasting and Social Change***. 137: 226–240.

Wu, C. X., Gao, Y. 2020. Research on the mechanism and effect of digital economy driving the development of low-carbon industry. ***Guizhou Social Science***, (11): 155-161. 2020.11.020.

Zhang, W., Liu, X., Wang, D., Zhou, J. 2022. Digital economy and carbon emission performance: Evidence at China's city level. ***Energy Policy***, 165, 112927.

Zhao, T., Zhang, Z., Liang, S. K. 2020. Digital economy, entrepreneurial activity and high-quality development-Empirical evidence from Chinese cities. ***Management World***, 36(10): 65-76.2020.0154.

Li, Z. G., Wang, J. 2022. How does the development of digital economy affect spatial carbon emissions in the context of economic agglomeration? ***Journal of Xi'an Jiaotong University (Social Science Edition)***, 42(05): 87-97.