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The Impact of China's Digital Trade on Carbon Emissions in ASEAN Countries

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ABSTRACT

Against the backdrop of deepening globalization, the widespread adoption and application of digital technologies are reshaping global trade patterns and providing new momentum for low-carbon economic cooperation. Based on panel data from 10 ASEAN countries for the period 2010–2020, this study investigates the role of digital trade in the trade-environment nexus. The findings reveal an inverted U-shaped relationship between digital trade and carbon emissions, which is explained through the scale effect, structural effect, and technological effect. Furthermore, the study examines the influence of economic development levels and industrial structures on this relationship, identifying significant heterogeneity. Countries with higher levels of economic development and more advanced industrial structures exhibit a more pronounced inverted U-shaped relationship between digital trade and carbon emissions.

KEYWORDS

Digital Trade; Carbon Emissions; ASEAN; Two-way Fixed-effect Model

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1. Introduction

A new generation of information technologies, represented by big data, cloud computing, the Internet of Things (IoT), and artificial intelligence (AI), has rapidly emerged as a transformative force in global trade and economic collaboration (Chen L., 2022). Digital trade is increasingly recognized as a key driver for advancing international trade and deepening economic and trade cooperation among nations (Ouyang R. et al., 2024). However, alongside the rapid industrial development in many countries, associated activities such as infrastructure construction and logistics have contributed significantly to environmental pollution. The detrimental effects of these developments are becoming increasingly apparent, making carbon emission reduction an urgent and challenging task for countries worldwide (Watts N. et al., 2016; Hansen J. et al., 2018). According to the International Energy Agency, ASEAN countries heavily rely on fossil fuels to meet their growing energy demands, a dependency that has been identified as a major vulnerability during the ongoing global energy crisis. Accelerating energy transitions in these countries is imperative. Compared to traditional goods trade, digital trade is characterized by the digitalization of trade objects, with virtual products forming the core of transactions and production processes leaning toward cleaner methodologies (Mingjie R., 2018). Consequently, digital trade has a lower environmental impact and plays a significant role in promoting low-carbon and environmentally friendly technologies (Pariyar A. et al., 2024). Furthermore, the growth of digital trade has diversified product categories, driving consumer demand for cleaner products and compelling enterprises to innovate and develop new products to meet evolving market demands (Liu H., 2020). The internationalization of digital trade further accelerates progress toward achieving zero growth in carbon emissions, enhancing global sustainability efforts (Wang Y. et al., 2023). In pursuit of sustainable economic development, an increasing number of countries along the Belt and Road Initiative have announced carbon neutrality targets, underscoring the urgency of integrating environmental sustainability into economic and trade strategies.

The Association of Southeast Asian Nations (ASEAN), the third-largest economy in Asia and the sixth-largest globally, is one of the world’s emerging economic centers. ASEAN is also China’s largest trading partner, a primary destination for outbound Chinese investment, and a key region for the Belt and Road Initiative (BRI). Under the framework of the Digital Silk Road, ASEAN serves as a critical platform for digital trade between China and countries along the BRI route. The trade relationship between ASEAN and China has consistently maintained a leading position. From 2009 to 2021, China has remained ASEAN’s largest trading partner, while ASEAN became China’s top trading partner in 2020 and 2021. Due to geographical proximity, cultural similarities, and the comparatively lower levels of digitalization in most ASEAN countries relative to China, ASEAN has become a preferred destination for Chinese online platforms seeking to expand their business models internationally. This relationship also provides ASEAN with valuable opportunities to gain practical experience in digital transactions through collaboration with China. Moreover, ASEAN's digital economy development is supported by a foundational governance framework, with countries like Singapore wielding significant international influence in establishing digital regulations. Studying the development and cooperation dynamics of China-ASEAN digital trade and formulating collaborative strategies can unlock the full potential of this partnership. It not only provides a reference model for fostering digital trade between China and other key regions along the Belt and Road but also drives the construction of the Digital Silk Road. Furthermore, joint initiatives with ASEAN can offer "China-style solutions," enhancing China's international discourse power in shaping digital trade regulations.

2. Literature Review

Since the 1990s, the acceleration of global economic integration has been accompanied by growing awareness of environmental issues, prompting increasing attention to the environmental impacts of trade (Antweiler et al., 2001; Copeland & Taylor, 2004). Some researchers argue that international trade facilitates the relocation of high-pollution industries to developing countries, posing significant short- and long-term environmental challenges for these nations (Shen Y., 2021; Liddle, 2018). Certain environmentalists even advocate for a "zero economic growth" model to protect ecosystems. Conversely, other scholars suggest that while trade may initially have negative environmental impacts, it can lead to long-term positive effects by enhancing energy efficiency, fostering technological innovation, and improving resource allocation (Li X. et al., 2024). Still, some studies posit a nonlinear relationship between trade and the environment, with economic development levels and foreign direct investment exerting asymmetric threshold effects on the environmental impact of trade (Xu S. C., 2019). This divergence has given rise to conflicting views, including "trade harms the environment," "trade benefits the environment," and "trade is environmentally neutral."

In recent years, the application of digital technologies in trade has injected new momentum into global low-carbon economic cooperation. Digital trade, characterized by virtualization and platformization based on information and communication technology, differs fundamentally from traditional trade. However, its environmental effects remain uncertain. There is currently no unified standard for defining and measuring digital trade, leading most researchers to conduct qualitative analyses. For example, studies have examined the development of digital trade (Romao P., 2024) and negotiation rules for digital trade agreements (Han J. et al., 2019), emphasizing its role as a key driver of national economic growth. Quantitative studies on the environmental impacts of digital trade are relatively limited. For instance, Steenblik and Grosso (2011) suggest that the adoption of low-carbon technologies relies on international trade in services, while Li X. et al. (2024), through an empirical analysis of data from 46 major global economies, found that digital service trade effectively reduces carbon emissions. Wang Y. (2023) analyzed data from 30 provinces in China, concluding that digital trade significantly contributes to reducing carbon emissions. However, these fragmented studies fail to provide a comprehensive understanding of the environmental impacts of digital trade.

Previous research has shown that traditional international trade impacts the environment through scale effects, structural effects, and technological effects, with the combined interaction of these mechanisms determining the overall impact (Grossman & Krueger, 1991). A report by UNCTAD on global digital trade highlights how digital trade has transformed traditional trade models and deepened industrial value chains worldwide. Digital trade transcends geographical limitations, giving rise to new forms such as cross-border e-commerce, overseas warehouses, and bonded warehouses, which have disrupted traditional trade and industries. This transformation has promoted the integration of various industries and driven industrial upgrading (Ma S. Z., 2018). Furthermore, digital technologies empower trade by fostering technological advancements, converting digital resource endowments into higher-level competitive advantages (Yu Y., 2023). This digitalization has enabled industries, including manufacturing, to achieve smart and digital upgrades, improving energy and resource efficiency, reducing energy consumption, and mitigating carbon emissions.

These findings suggest that the development of digital trade could alter the traditional environmental impacts of trade. However, limited research has explored its effects on carbon emissions from the perspectives of scale, structure, and technology. This study aims to fill that gap by examining digital trade's influence on carbon emissions through these three dimensions.

3. Theoretical Analysis and Research Hypothesis

3.1. Direct Effects of Digital Trade on Carbon Emissions

This study examines the deep development of digital trade from the perspective of digital infrastructure. Digital infrastructure is critical for achieving sustainable development while providing essential support for the growth of digital trade (Guo Q. et al., 2022). During the initial stages of digital trade development, as trade models undergo digital transformation, traditional infrastructure often becomes inadequate to support the import and export of digital goods. This necessitates large-scale investment in digital infrastructure, which can lead to a short-term increase in energy consumption and carbon emissions. However, because digital trade predominantly relies on data and technology for the transmission of goods and services, it significantly reduces the intermediate transportation processes involved in traditional trade, thereby lowering variable costs—particularly the “iceberg” costs of transportation. As a result, digital trade promotes rapid growth in trade volumes, which in the early stages may lead to an increase in carbon emissions due to the expansion of digital infrastructure and trade activities.

As digital trade matures, two key developments contribute to mitigating its carbon emissions. First, as digital infrastructure becomes more robust, the energy consumption and carbon emissions associated with infrastructure and equipment upgrades decline significantly. Second, the ongoing development of digital trade drives enterprises to adopt energy-saving and emission-reducing practices across all stages of research and development (R&D), production, and trade. Digital trade regulations and systems are gradually being established, with higher technical standards for digital products compelling enterprises to increase R&D investments to meet market demands and trade norms. Furthermore, digital trade is characterized by the virtualization of physical goods and the shift toward cleaner production processes. The establishment of digital trading platforms also transcends geographical and cultural barriers, significantly reducing costs associated with information search, marketing, and market development. This reduced reliance on traditional logistics models lowers carbon dioxide emissions during trade transactions.

In this context, digital trade fosters continuous digital transformation among enterprises, creating a virtuous cycle of carbon reduction across the "R&D-production-trade" value chain. Based on this analysis, the following research hypothesis is proposed:

Hypothesis 1: The impact of digital trade on carbon emissions follows an inverted U-shaped relationship, initially promoting emissions before subsequently reducing them.

3.2. heading Channels Through Which Digital Trade Affects Carbon Emissions

Building on the general equilibrium model of trade and the environment proposed by Grossman and Krueger (1992), this study incorporates the intrinsic attributes of digital trade to explore its impact channels on carbon emissions.

3.2.1. The Scale Effect of Digital Trade

Digital trade integrates digital technologies with traditional trade, characterized by virtualization, platformization, intensification, personalization, centralization, and eco-friendliness (Ma S. Z. et al., 2018). The development of digital trade reduces production and transaction costs, thereby accelerating the globalization of trade (Liu Q., 2022). In its initial stages, digital trade may drive the growth of traditional trade, expanding trade volumes and leading to increased carbon emissions. However, as digital trade deepens, it gradually replaces traditional trade. New forms of trade, such as cross-border e-commerce and overseas warehouses, reduce the reliance on energy-intensive traditional trade models. Digital trade facilitates the digitalization of goods and services, enabling transactions via data transmission and reducing energy consumption in production processes. This shift mitigates the environmental negative externalities caused by traditional trade expansion.

In addition to traditional physical goods, digital trade encompasses digital products, services, knowledge, and information. These attributes enhance real income through price competition, price reductions, and diversified product supplies, ultimately increasing consumer welfare (Sheng B., 2020). With rising household incomes, demand for digital appliances grows. These appliances better align with consumer preferences, encouraging enterprises to produce cleaner products and thereby gaining international competitiveness. This dynamic improves the environmental benefits of trade expansion. Based on this, the following hypothesis is proposed:

Hypothesis 2: Digital trade impacts carbon emissions through the scale effect.

3.2.2. The Structural Effect of Digital Trade

The intensification characteristic of digital trade enhances its structural effect on carbon emissions. By centralizing inputs and management, digital trade improves global resource allocation efficiency and reduces energy consumption in production and management processes. Additionally, digital trade optimizes resource endowments through comparative advantage and better utilization of resources, shifting production factors from primary industries to secondary and tertiary sectors. This enhances resource allocation efficiency and promotes a more balanced industrial structure.

Digital trade, exemplified by e-commerce and internet-based services, exerts a "crowding-out effect" on energy-intensive, high-emission industries, fostering industrial optimization. As polluting and energy-intensive enterprises phase out, production shifts to low-emission, low-energy service sectors, curbing overall carbon emissions. Moreover, the expansion of digital trade diversifies trade types and increases consumer demand for clean products, motivating companies to develop new, environmentally friendly products to meet varied market needs. This process optimizes China's consumption demand and trade structure by reducing demand for high-pollution, high-energy imports while increasing the proportion of clean goods. Based on this, the following hypothesis is proposed:

Hypothesis 3: Digital trade impacts carbon emissions through the structural effect.

3.2.3. The Technological Effect of Digital Trade

The technological effect of digital trade further influences carbon emissions. To gain a competitive edge, digital trade requires enterprises to possess core digital technologies, encouraging increased investment in R&D and fostering global exchanges in advanced production techniques and management practices. This accelerates the adoption of digital technologies across industries, driving enterprises toward technology- and knowledge-intensive models, improving resource allocation efficiency, and reducing carbon emissions.

Digital trade's centralization characteristic allows low-technology enterprises to gradually participate through learning and technological spillovers. By leveraging digital technologies, digital trade facilitates the exchange of digital goods and services, enhancing technological spillover effects. Countries with lower technological levels can attract foreign investment to acquire advanced clean production technologies and management expertise, reducing energy consumption.

Furthermore, the ecological nature of digital trade integrates industries into a unified supply chain management system encompassing procurement, warehousing, processing, distribution, and information services. Digital trading platforms, powered by artificial intelligence, precisely monitor market demand changes and evaluate energy production and consumption comprehensively. These platforms improve energy utilization efficiency and guide enterprises toward intelligent and green development. Based on this, the following hypothesis is proposed:

Hypothesis 4: Digital trade impacts carbon emissions through the technological effect.

4. Empirical Analysis

4.1. Model Construction

To test the proposed hypotheses, this study establishes the following bidirectional fixed-effects models. First, Model (1) is constructed to empirically analyze the inverted U-shaped effect of digital trade on carbon emissions in

ASEAN countries:

$$CO_{2_{it}} = \alpha_0 + \alpha_1 digital_{it} + \alpha_2 digital_{it}{}^2 + \sum \alpha_m Z_{mit} + \mu_i + \lambda_t + \varepsilon_{it} \tag{1}$$

Next, Models (2) and (3) are formulated to examine the channels through which digital trade affects carbon emissions:

$$M_{it} = \beta_0 + \beta_1 digital_{it} + \beta_2 digital_{it}{}^2 + \sum \beta_m Z_{mit} + \mu_i + \lambda_t + \varepsilon_{it} \tag{2}$$

$$CO_{2_{it}} = \gamma_0 + \gamma_1 digital_{it} + \gamma_2 digital_{it}{}^2 + \sum \alpha_m Z_{mit} + \mu_i + \lambda_t + \varepsilon_{it} \tag{3}$$

In these models, i and t represent the country and year, respectively. $CO2_{it}$ denotes the carbon emissions of country i in year t, while $digital\_trade_{it}$ represents the level of digital trade. Mitrefers to the scale, structural, and technological effects of foreign direct investment (FDI) for country i in year t. Zmit represents a series of control variables, μi denotes individual fixed effects， λt indicates time fixed effects, and εit is the random error term.

4.2. Sample Selection and Data Description

The ASEAN member countries primarily include ten nations, but due to the lack of data on digitally deliverable service trade for Brunei, the total ICT product import and export volume is used as a substitute. Data on carbon dioxide emissions are sourced from the EIA database, digital trade data from the UNTCTAD database, and data on mediating variables and control variables from the WDI database. To ensure the balance of panel data, some missing values were processed using linear interpolation.

The dependent variable is the carbon dioxide (CO_2) emissions of ASEAN countries. Higher CO_2 emissions hinder the achievement of carbon neutrality targets in these countries. The core explanatory variable is digital_trade, As defined by UNTCTAD, digital trade includes goods (ICT goods) and services traded using information and communication technology, comprehensively reflecting the level of digital trade development in various countries, and widely adopted by scholars. Therefore, this study uses the value of digitally deliverable service trade in the UNTCTAD database as a measure of digital trade.

To examine the channels through which digital trade affects carbon emissions, this study incorporates variables such as the level of goods trade(goodstrade), income level(income), industrial structure upgrading(is), trade structure optimization(service), innovation input(imICT), and innovation output(exICT). These variables are used to verify whether digital trade influences carbon emissions through scale effects, structural effects, and technological effects. Drawing on existing research, other factors influencing carbon emissions are controlled for: Per capita GDP(pdgp): There is a strong link between a country's per capita GDP and carbon emissions. Population density(people): Higher population density often amplifies per capita energy consumption and the scale effects of economic development. Urbanization rate(urban): Rapid urbanization and industrialization place significant pressure on the environment. Resource endowment(source): A higher proportion of renewable energy consumption leads to lower carbon dioxide emissions. Industrial base(industrial): Countries with stronger industrial foundations may generate more carbon emissions during production.

The definitions of the main variables and their descriptive statistics are presented in Table 1.

Table 1. Variable Description and Descriptive Statistics.

Variable			Indicator Description	Variable Symbol	Mean	Standard Error	Minimum	Maximum
Dependent Variable		Carbon Emissions	Carbon Emissions (in thousand tons)	CO_2	109,338	155,234	244.1	605,291
Core Explanatory Variable		Level of Digital Trade	Value of Digitally Deliverable Service Trade (in million USD)	detigal	24,464	47,922	1.598	252,499
Mediating Variables		Per Capita GDP	Per Capita GDP (in USD)	pgdp	11,280	17,836	765.2	66,837
		Population Density	Population Density (number of people per square kilometer of land area)	people	825.4	2,190	27.40	7,966
		Urbanization Rate	Proportion of Urban Population to Total Population (%)	urban	40.62	28.16	0.709	100
		Resource Endowment	Share of Renewable Energy Consumption in Total Final Energy Consumption (%)	reenergy	29.16	23.59	0	84.93
		Industrial Foundation	Proportion of Industrial Value Added to GDP (%)	industry	34.74	11.94	9.134	73.67
Mediating Variable	Scale Effect	Goods Trade Level	Ratio of Total Goods Trade (Imports and Exports) to GDP (%)	goodstrade	116.4	81.46	11.86	379.1
		Income Level	Ratio of Income to GDP (%)	income	51.83	59.99	7.576	345.0
	Structural Effect	Upgrading of Industrial Structure	Proportion of Service Value Added to GDP (%)	service	48.76	11.33	27.36	72.02
		Optimization of Trade Structure	Ratio of Service Trade to GDP (%)	servicetrade	27.99	29.87	3.064	147.4
	Technological Effect	Innovation Output	Export of Information and Communication Technology (ICT) Services (as a percentage of total service exports)	exICT	10.45	12.11	0.0130	50.86
		Innovation Input	Import of Information and Communication Technology (ICT) Products (as a percentage of total product imports)	imICT	12.33	9.554	1.113	32.85

4.3. Benchmark Regression Results

The benchmark regression results for the impact of digital trade on carbon emissions are shown in table 2. With the gradual inclusion of control variables, the coefficient of the linear term is positive, while the coefficient of the quadratic term is negative, and both pass the significance level test, indicating a clear inverted U-shaped relationship. The results show that in the initial stage of development, a large amount of digital infrastructure in ASEAN countries leads to an increase in carbon emissions. However, as digital trade advances, the entire process of "R&D - production - trade" generates a carbon reduction effect for enterprises, thereby reducing carbon emissions. To rigorously validate the existence of the inverted U-shaped relationship, this study conducts a U-test. The calculated turning point is 0.1725, which falls within the sample range [0.00016, 25.2499] and shows that the inverted U relationship is significant at the 1% level.

Table 2. Benchmark Regression Results.

Variables	(1) CO_2	(2) CO_2	(3) CO_2	(4) CO_2	(5) CO_2
detigal	0.1184^{**}	0.1429^{**}	0.1307^{**}	0.1274^{**}	0.1257^{**}
	(0.0488)	(0.0484)	(0.0471)	(0.0480)	(0.0490)
detigal ^{2}	-1.8800^{***}	-1.6664^{**}	-1.3266^{**}	-1.6424^{**}	-1.6280^{**}
	(0.5311)	(0.5234)	(0.5235)	(0.5955)	(0.6026)
pgdp	1.2010^{***}	1.1562^{***}	1.0293^{***}	1.0755^{***}	1.0489^{***}
	(0.1724)	(0.1686)	(0.1704)	(0.1820)	(0.2224)
people		4.3632^{**}	6.6607^{***}	6.0664^{**}	6.0791^{**}
		(1.7375)	(1.8974)	(1.9766)	(1.9883)
urban			1.3832^{**}	1.1161^{*}	1.1760^{*}
			(0.5266)	(0.5794)	(0.6485)
reenergy				0.1294	0.1333
				(0.1155)	(0.1176)
industry					0.0485
					(0.2309)
Individual Effects	YES	YES	YES	YES	YES
Time Effects	YES	YES	YES	YES	YES
_cons	-0.7910	-22.4304^{**}	-37.0950^{***}	-33.9491^{**}	-34.1485^{**}
	(1.5225)	(8.7436)	(10.1469)	(10.5763)	(10.6765)
N	110	110	110	110	110
R^2	0.748	0.764	0.781	0.784	0.784

Standard errors in parentheses. $^{*}p<0.10$, $^{**}p<0.05$, $^{***}p<0.001$

5. Examination of Mediating Channels

5.1. Scale Effect

Goods Trade Crowding-Out Channel. This study uses the ratio of total goods trade (imports and exports) to GDP (%) as a proxy variable for the goods trade crowding-out channel. The first column of table 3 shows that digital trade exhibits an inverted U-shaped impact on traditional trade at the 10% significance level. Digital trade initially promotes the development of traditional goods trade but later replaces traditional goods, thereby inhibiting the growth of traditional trade.

Income Level Improvement Channel. This study uses the ratio of income to GDP (%) as a proxy variable for income level in ASEAN countries. The third column shows that digital trade in ASEAN countries promotes an increase in income levels. With the establishment of digital infrastructure and the accumulation of digital talent, income levels are boosted. The fourth column indicates that as income increases, carbon emissions are suppressed. Overall, digital trade in ASEAN countries facilitates income level improvement and reduces carbon emissions.

Table 3. Results of the Scale Effect of Digital Trade.

Variables	(1) goodstrade	(2) CO_2	(3) income	(4) CO_2
goodstrade		-0.0041**		
		(0.0014)		
income				-0.2340*
				(0.1397)
detigal	9.1191**	0.1286**	0.0660*	0.1411**
	(3.4622)	(0.0444)	(0.0365)	(0.0494)
detigal^2	-7.7883*	-0.9836*	1.9555***	-1.1696*
	(0.42778)	(0.5200)	(0.4512)	(0.6562)
Control Variables	YES	YES	YES	YES
Individual Effects	YES	YES	YES	YES
Time Effects	YES	YES	YES	YES
_cons	688.3513	-38.8904***	0.0660*	-42.7661***
	(752.4762)	(9.2679)	(0.0365)	(11.7525)
N	110	110	110	110
R^2	0.433	0.831	0.810	0.791

*Standard errors in parentheses. *p<0.10, **p<0.05, ***p<0.001*

5.2. Technological Effect

Innovation Output Channel. This study uses the export of information and communication technology (ICT) services (as a percentage of total service exports, BoP) as a proxy variable for innovation output. The first column shows that digital trade can promote the export of information technology products, which has a positive effect on enhancing the innovation output of ASEAN countries. The second column indicates that ICT product exports lead to increased carbon emissions. Overall, as digital trade advances, carbon emissions are suppressed.

Innovation Input Channel. This study uses the import of information and communication technology (ICT) products (as a percentage of total product imports) as a proxy variable for the innovation input channel. The third column shows that digital trade can suppress ICT product imports. As digital trade develops, it enhances the innovation capacity of ASEAN countries, increases innovation output, and reduces ICT product imports. The fourth column shows that ICT product imports contribute to increased carbon emissions, as the growing scale of ICT product imports involves more enterprises, thereby overall increasing carbon emissions (table 4).

Table 4. Results of the Technological Effect of Digital Trade.

Variables	(1) exICT	(2) CO_2	(3) imICT	(4) CO_2
exICT		0.0487*		
		(0.0267)		
imICT				0.2447**
				(0.0813)
detigal	0.5748**	0.6211*	-3.6084**	-0.2269***
	(0.2295)	(0.3455)	(1.2214)	(0.0632)
detigal ^{2}	-0.0127*	-1.0967*	97.3812***	4.8188**
	(0.0066)	(0.6328)	(28.4241)	(1.8215)
Control Variables	YES	YES	YES	YES
Individual Effects	YES	YES	YES	YES
Time Effects	YES	YES	YES	YES
_cons	11.2744	3.6311**	-65.5689**	-16.2153
	(31.9416)	(1.6425)	(21.1674)	(10.6229)
N	110	110	110	110
R^2	0.354	0.805	0.457	0.836

*Standard errors in parentheses. *p<0.10, **p<0.05, ***p<0.001*

5.3. Structural Effect

Industrial Structure Upgrading Channel. This study uses the ratio of service value added to GDP (%) as an indicator to measure the degree of industrial structure upgrading. The table shows that the impact of digital trade on industrial structure upgrading exhibits an inverted U-shaped relationship of "first accelerating, then inhibiting." Every industry goes through a process from growth to decline, and in the future, it is necessary to make appropriate adjustments to the mode of industrial development to adapt (Zhang Huiheng, 2004). The second column indicates that industrial structure upgrading in ASEAN will lead to an increase in CO2 emissions, and therefore, it is necessary to promote industrial structure upgrading through the development of digital trade to effectively reduce CO2 emissions.

Table 5. Results of the Structural Effect of Digital Trade.

Variables	(1) service	(2) CO_2	(3) is	(4) CO_2
lnservice		1.3311*		
		(0.6861)		
servicetrade				0.0058***
				(0.0016)
detigal	0.0001*	0.0703*	0.1508**	-0.3320***
	(0.0001)	(0.0374)	(0.0482)	(0.0934)
detigal^2	-0.0299*	-0.8651*	1.8559**	5.9222**
	(0.0178)	(0.5006)	(0.8579)	(2.1674)
Control Variables	YES	YES	YES	YES
Individual Effects	YES	YES	YES	YES
Time Effects	YES	YES	YES	YES
_cons	74.5866***	-44.7775***	-1.7559	3.8600**
	(13.2302)	(11.9019)	(2.3592)	(1.5573)
N	110	110	110	110
R^2	0.809	0.787	0.440	0.834

*Standard errors in parentheses. *p<0.10, **p<0.05, ***p<0.001*

Trade Structure Optimization Channel. This study uses the ratio of service trade to GDP (%) as a proxy variable for trade structure optimization. The third column shows that both the linear and quadratic coefficients of digital trade are positive, indicating that digital trade in ASEAN promotes trade structure optimization. The fourth column indicates that the optimization of ASEAN's trade structure promotes CO2 emissions; however, digital trade can suppress CO2 emissions. Therefore, in the context of digitization, the application of digital technology benefits high-carbon industries in ASEAN countries' service sectors. Changes in trade structure largely enhance the competitiveness of high-carbon products in ASEAN countries, leading to increased CO2 emissions (table 5).

5.4. Robustness and Endogeneity Tests

Robustness Check. To verify the reliability of the research results, this study employed the following robustness check methods. First, interaction fixed effects of individuals and time were used to control for country-specific factors that may evolve over time. By introducing dummy variables for the product of individual and time, the impact of unobservable factors that change with the variation in countries and time on the research results can be controlled. Next, the core explanatory variable was changed, and per capita CO2 emissions were used to replace the original dependent variable to rule out potential impacts of the choice of dependent variable on the regression results. Overall, the results of the robustness checks are generally consistent with the benchmark regression analysis. Although the magnitude of the core explanatory variable's coefficient varied slightly, its sign and significance level remained unchanged, indicating that the empirical results of this study are robust.

Endogeneity Issue Discussion. During the benchmark regression analysis, although stepwise regression and the control of fixed effects for countries and years can alleviate endogeneity issues to some extent, the following potential endogeneity concerns should still be noted. First, there is a possibility of bidirectional causality: digital trade may impact carbon emissions, and countries with high carbon emissions may accelerate their industrial digital transformation due to international pressure, which in turn could affect digital trade. To address this, this study used the lagged data of digital trade as an instrumental variable and conducted regression analysis using two-stage least squares (2SLS). According to the results shown in column (3) of Table 6, the linear coefficient of digital trade is significantly positive, while the quadratic coefficient is significantly negative, and the instrumental variable passed both the over-identification test and the weak instrument test.

Table 6. Results of Robustness and Endogeneity Tests.

Variables	Robustness Check		Endogeneity Issue Discussion	
	PCO_2 (1) Replacement of Core Explanatory Variable	CO_2 (2) Control for Interaction Between Time and Individual	CO_2 (3) 2sls	CO_2 (4) Exogenous Event Shock
detigal	0.1994**	0.0687**	0.5227***	0.0638*
	(0.0716)	(0.0346)	(0.0652)	(0.0359)
$detigal^2$	-0.2367*	-0.0011*	-0.3944***	-0.1517**
	(0.1273)	(0.0006)	(0.1091)	(0.0510)
B&R				0.1513
				(0.3526)
Control Variables	YES	YES	YES	YES
Individual Effects	YES	YES	YES	YES
Time Effects	YES	YES	YES	YES
LMstatistic			85.116	
WaldF			348.900	
_cons	-1.9023	-61.3494*	-3.6781	-4.4504
	(3.1527)	(33.9287)	(2.3578)	(11.3109)
N	110	110	110	110
R^2	0.527	0.806	0.911	0.795

Standard errors in parentheses. $^*p<0.10$, $^{**}p<0.05$, $^{***}p<0.001$

Additionally, considering that the sample period of this study covers 2010 to 2020, and the "Belt and Road Initiative" (B&R) was officially launched in 2015, which might have caused fluctuations in digital trade and carbon emissions levels in the sample countries, this study created a dummy variable for the B&R initiative, setting it to 0 before 2015 and 1 from 2015 onwards. However, according to the results in column (4) of Table 6, the B&R variable did not pass the significance test, indicating that the implementation of the Belt and Road Initiative did not have a significant impact on the environmental issues of the countries along the route.

6. Heterogeneity Analysis

6.1. Heterogeneity in Economic Development Level

When considering the differences in economic development levels, according to data from the China Academy of Information and Communications Technology, developed economies accounted for 76.1% of the global digital services export market in 2019, three times the share of developing and transition economies. This disparity highlights the importance of heterogeneity analysis, especially for policy formulation and practical guidance. The heterogeneity regression results in Table 7 show that digital trade in ASEAN has a significant inverted U-shaped impact on carbon emissions. Specifically, the results in column (1) indicate that the coefficient for economic development level is positive at the 1% significance level. Column (2) shows that the coefficient for the interaction between the linear term of digital trade and economic development level is negative at the 1% significance level, while the quadratic interaction term is positive, suggesting that higher economic development levels strengthen the inverted U-shaped effect of digital trade on carbon emissions. This may be because countries with higher levels of economic development have more advanced digital technologies and stronger capacities to integrate high-tech industries. Through digital trade with developed countries, these nations can more effectively optimize resource allocation and improve efficiency, thereby amplifying the impact of digital trade on carbon emissions. Conversely, regions with lower economic development levels have weaker industrial systems, limiting the technological transformative capacity triggered by digital trade.

Table 7. Results of Heterogeneity Analysis by Economic Development Level and Industrial Structure Level.

Variables	Economic Development Level		Industrial Structure Level	
	(1) CO_2	(2) CO_2	(3) CO_2	(4) CO_2
detigal	0.1257**	-0.3021**	0.1257**	0.0585*
	(0.0490)	(0.0000)	(0.0490)	(0.0332)
detigal^2	-1.6280**	0.5999**	-1.6280**	-0.8334
	(0.6026)	(0.2249)	(0.6026)	(0.6625)
pgdp	1.0489***	-0.2030*		
	(0.2224)	(0.0000)		
industry			0.0485	-0.9430***
			(0.2309)	(0.2061)
detigal&pgdp		3.3101***		
		(0.4960)		
detigal^2&pgdp		-1.6245***		
		(0.2477)		
detigal&industyr				-1.1099**
				(0.3487)
detigal^2&industyr				5.6095*
				(3.2517)
Control Variables	YES	YES	YES	YES
Individual Effects	YES	YES	YES	YES

Time Effects	YES	YES	YES	YES
_cons	-34.1485**	20.8534***	-34.1485**	0.5393
	(10.6765)	(1.7331)	(10.6765)	(1.4916)
N	110	110	110	110
R^2	0.784	0.755	0.784	0.796

6.2. Heterogeneity in Industrial Structure Level

Data analysis from Table 7 reveals the impact of industrial structure level on the relationship between digital trade and carbon emissions in ASEAN countries. Specifically, the results in column (3) show that countries with more developed industrial structures tend to have higher carbon emissions. This may be due to the fact that, in the context of increasing global trade risks, ASEAN countries with better industrial structures are better able to attract investment and industrial production from developed countries, leading to increased carbon emissions. Analysis in column (4) indicates that the improvement of industrial structure exacerbates the inverted U-shaped effect of digital trade on carbon emissions. This may be because, during the early stages of digital trade development, countries with more developed industrial structures can more effectively adapt to the rules and standards of digital trade, reduce transaction frictions, and promote trade liberalization, which increases carbon emissions. However, Jansen (2001) noted that as digital trade further develops, countries with better industrial structures are more likely to attract high-tech industries and accelerate the optimization of their industrial structures through digital transformation, thus contributing to a reduction in carbon emissions.

7. Research Conclusions and Policy Recommendations

After analyzing the impact of digital trade on carbon emissions, this study explores the importance of digital trade development in ASEAN countries for promoting high-quality development in the region and achieving global carbon neutrality goals, and draws the following conclusions: Digital trade in ASEAN countries has an inverted U-shaped effect on carbon emissions, with emissions initially increasing and then decreasing. This finding holds true even after multiple robustness checks. ASEAN's digital trade influences carbon emissions through scale effects, structural effects, and technological effects. The scale effect is mainly reflected in the substitution of traditional trade and income level improvements, the structural effect is seen in the optimization of industrial and trade structures, and the technological effect is evident in promoting national innovation output, although the direct impact of innovation input is less pronounced. For ASEAN countries with higher economic development levels and more optimal industrial structures, the inverted U-shaped impact of digital trade on carbon emissions is more significant. Based on these findings, this paper proposes the following policy recommendations:

Develop Digital Trade to Promote Green ASEAN Construction: ASEAN countries should accelerate the development of a new economic model centered on digital trade, promote the digital transformation of traditional trade, and leverage digital tools such as big data, cloud computing, and artificial intelligence to strengthen digital infrastructure and increase digital levels and network coverage. This will create conditions for the development of digital trade, shifting its carbon emission effects from a promoting phase to a suppressing phase. By leading the development of digital trade, ASEAN can make green development the central theme of regional cooperation and establish itself as an important force in global ecological civilization construction.

Tap into New Drivers of High-Quality Development in ASEAN: ASEAN countries should utilize digital platforms to seek economic and trade cooperation opportunities with developed countries and regions such as RCEP, continuously guiding the economy toward green and low-carbon development. While expanding the scale of digital trade, countries should strengthen industrial digital transformation, increase the share of the service sector, and enhance international cooperation in green supply chains to improve the lifecycle of green production and consumption. Digital trade can facilitate the intelligent upgrading of traditional industries. Additionally, countries should develop high-quality green product trade, strengthen the import and export of energy-saving and environmentally friendly products and services, promote green investments, and optimize trade structures.

Continuously Optimize the Industrial Structure of ASEAN Countries: ASEAN countries should deepen policy communication, improve digital governance and regulatory measures, and actively participate in the development of international green standards. They should integrate green and low-carbon principles into all aspects and processes of economic and social development, align with green standards adopted by co-building ASEAN nations, and seek consensus with countries worldwide on addressing environmental pollution. Measures such as environmental taxes and the improvement of carbon trading systems should be implemented to provide an industrial structure conducive to digital trade development, attract foreign high-tech industries, and strengthen the carbon reduction effect of digital trade. This will help accelerate the formation of a green development pattern in ASEAN and contribute intelligence and strength to achieving global carbon neutrality goals.

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Conflict of interest

All the authors claim that the manuscript is completely original. The authors also declare no conflict of interest.

Author contributions

Sen Wang: Conceptualization, Methodology, Supervision, Formal analysis, Writing - review & editing. Jinpei Cao: Software, Visualization, Funding acquisition, Writing – original draft, Writing - review & editing, Formal analysis. Xudong Hu: Conceptualization, Methodology. Pu Hao: Writing - review & editing.

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