

Study on the Impact of Enterprise Export Technological Complexity on Carbon Emissions: Micro-level Evidence from Chinese Listed Companies

Shiyi Yu*, Nan Ding, Yating Deng

School of International Economics and Politics, Jiangxi University of Finance and Economics,
Nanchang, Jiangxi, 330000, China

Abstract

Against the backdrop of an accelerating digital economy and with new productive forces emerging as a core driver, the relationship between export technological sophistication and carbon emissions is gaining renewed importance. Research into its underlying synergistic mechanisms holds critical practical relevance for elucidating how technological upgrading drives green transformation and promotes high-quality exports. This study empirically examines the impact of export technological complexity on carbon emissions at the micro-firm level using data from Chinese A-share listed companies from 2013 to 2022, while exploring its underlying mechanisms and heterogeneous characteristics. Findings reveal that increased enterprise export technological complexity significantly curbs carbon emissions, a conclusion that holds after endogeneity treatment and robustness tests. Mechanism analysis shows that increasing R&D investment, alleviating financing constraints, and improving green total factor productivity are three key mediating pathways for enterprises to improve export technological sophistication and achieve carbon emission reduction. Heterogeneity research shows that this emission reduction effect is more significant in state-owned enterprises, manufacturing enterprises, and small and medium-sized enterprises. This study not only fills a gap in micro-level empirical research on the relationship between export technological sophistication and corporate carbon emissions, but also uncovers its underlying transmission mechanisms. It provides theoretical foundations and practical guidance for different types of enterprises to simultaneously enhance technological competitiveness and pursue green development, thereby contributing to the achievement of China's carbon peaking and carbon neutrality goals.

Keywords

Export Technological Complexity; Carbon Emissions; Green Total Factor Productivity; Financing Constraints; R&D Investment.

1. Introduction

In the global challenge of addressing climate change, controlling carbon emissions has become a core issue for humanity's common future. International trade, as a key vehicle for global resource allocation, serves a dual function: it acts as both a channel for carbon emission transfer and a bridge for the diffusion of green technologies. Since the adoption of the United Nations Framework Convention on Climate Change in 1992, a low-carbon economy has gradually emerged as the dominant paradigm for global development. Against this backdrop, China's "Dual Carbon" goals (peaking emissions by 2030 and achieving carbon neutrality by 2060) represent more than just a national commitment to its international responsibilities; they also provide a significant case study for observing the global green transformation. With the digital economy rising as a new growth engine, the concept of green trade is evolving profoundly: it is

moving beyond the traditional optimization of commodity structures to encompass new dimensions such as digital trade technologies, the foundational development of green industrial chains, and external regulatory frameworks like the Carbon Border Adjustment Mechanism (CBAM). This is especially true in the current context of a profoundly reshaped global trade landscape and intensifying green competition, where enhancing technological sophistication is paramount for decoupling economic growth from carbon emissions.

The technological complexity of corporate exports, being an intensive reflection of a nation's technological capabilities in international trade (Li and Wang, 2024), is a crucial indicator for measuring its export quality and position in the global division of labor. Therefore, enhancing the technological complexity of corporate exports is not only a key pathway to building a trade powerhouse but also a necessary step toward achieving high-quality economic development and addressing "green trade barriers." This imperative has been further reinforced by China's national strategy for developing new quality productive forces. A 2024 policy document—the "Implementation Opinions on Promoting Future Industrial Innovation and Development" jointly issued by the Ministry of Industry and Information Technology and seven other departments—explicitly calls for technology upgrading to drive green and low-carbon industries, underscoring technology's pivotal role in both economic growth and the realization of the "Dual Carbon" goals. As key actors in both export trade and carbon reduction, enterprises now face a synergistic imperative to simultaneously pursue enhanced competitiveness through technological upgrading and green development through carbon emission reductions. However, with the EU's Carbon Border Adjustment Mechanism (CBAM) coming into effect and low-carbon standards in international supply chains becoming increasingly stringent, a relatively low level of export technological complexity could not only constrain China's influence in shaping global green trade rules but also expose it to the risk of a green lockout. Currently, literature directly examining the impact of China's export technological complexity on corporate carbon emissions is scarce, though related research offers valuable insights. Against this backdrop, and as the global race toward carbon neutrality intensifies post-2025 alongside the growing role of digital technologies in facilitating emission reduction, exploring how to leverage increased export technological complexity to boost corporate competitiveness and achieve synergistic low-carbon growth has become an urgent priority. This approach not only helps navigate emerging green trade barriers but also provides theoretical and policy support for building a distinctively Chinese green trade system.

Although research on the technological complexity of Chinese exports has grown substantially, most studies are concentrated at the macro level (e.g., national or industrial), while micro-level, firm-specific mechanisms remain relatively underexplored. Research indicates that technological complexity significantly promotes economic growth, a finding well-supported by empirical studies (Du and Li, 2019). Further studies have identified a U-shaped relationship between the technological complexity of manufacturing exports and green total factor productivity, wherein surpassing a certain threshold effectively promotes low-carbon development through both technological and structural effects (Tu et al., 2023; Bao, 2024). However, enhancing the technological complexity of exports may exacerbate income inequality (Ma, 2024).

In existing research, technological factors emerge as the core variables influencing corporate carbon emissions, which can be categorized into three pathways: First, digital transformation facilitates carbon emission reduction. Corporate digital transformation can indirectly reduce carbon emissions by optimizing energy usage and stimulating green technological innovation (such as increasing the number of green patents) (Wang and Wang, 2022). Second, R&D and technology application for emissions reduction, taking robot adoption as an example, studies indicate that robot applications can reduce corporate carbon emissions by promoting the growth of R&D investment and enhancing green technology capabilities (Li and Tian, 2023);

Studies examining new productive forces reveal that these forces can significantly reduce corporate carbon emissions through technological upgrades and optimized resource allocation. Furthermore, policies from national-level big data comprehensive pilot zones can positively regulate this emission reduction effect through signaling effects (Zhang and Yu, 2025). Third, green technological innovation reduces emissions. Green technological innovation can significantly improve corporate carbon emission performance (Li and Li, 2024).

Existing literature on the relationship between export technological complexity and carbon emissions can be broadly categorized into three streams. First, industry-level studies using industry panel data examine the impact mechanisms and heterogeneity; findings indicate that in industrial sectors, export technological complexity exerts a significant negative effect on carbon emissions, with emission reduction effects intensifying after exceeding environmental regulation or economic development thresholds (Burki and Dahlstrom, 2017). Research shows that in the 28 sub-sectors of the manufacturing industry, technological upgrading and foreign direct investment (FDI) can promote carbon emission reduction, and industry heterogeneity is a key factor explaining divergent findings (Wang et al., 2017). Second, macro-level studies analyze trade-embedded carbon emissions and regional disparities from a country perspective: using multi-regional input-output models, they find that increased export technological complexity suppresses trade-embedded carbon emissions (Wu and Pan, 2018). Another strand of research argues that importing technologically complex goods reduces industrial carbon emissions through R&D, while environmental regulations show a single threshold effect (Li and Qian, 2021). Third, research examining multi-factor interactions explores the interplay between technological complexity and other economic factors: findings indicate that in the context of the digital economy, the interaction between industrial technological complexity and the digital economy exerts a U-shaped influence on industrial carbon emissions. This interaction itself has a suppressing effect, but only after the digital economy surpasses a certain threshold (Wang et al., 2025).

The existing literature on the relationship between export technological sophistication and carbon emissions is characterized by three primary limitations: an over-reliance on macro-level analyses, insufficient examination of micro-level mechanisms, and inadequate consideration of heterogeneity. To address these gaps, this study empirically investigates the impact of export technological sophistication on carbon emissions from a micro-level perspective, utilizing data from Chinese A-share listed companies over the period 2013–2022. The key contributions of this study are threefold. First, it shifts the research focus from the industry to the enterprise level, thereby addressing the scarcity of micro-empirical evidence. Second, it develops a mechanism analysis framework encompassing R&D investment, financing constraints, and green total factor productivity to elucidate the pathways through which export technological sophistication affects carbon emissions. Third, it conducts heterogeneity tests based on ownership type, industry characteristics, and firm size, uncovering heterogeneous effects across different groups and informing the design of more targeted environmental and economic policies globally. Theoretically, this study bridges a critical gap in the literature, which has predominantly focused on macro-level analysis at the expense of micro-level investigation, and uncovers the underlying transmission mechanism through which export technological sophistication influences corporate carbon emissions. Practically, the findings not only contribute to China's "Dual Carbon" goals (carbon peak and carbon neutrality) but also provide actionable insights for countries worldwide in fostering enterprises that successfully balance technological competitiveness with environmental sustainability.

2. Theoretical Analysis and Research Hypotheses

2.1. Core Direct Effect Hypothesis: The Direct Relationship between Exported Technology Complexity and Corporate Carbon Emissions

The existing literature on the relationship between export technological sophistication and carbon emissions suffers from three key limitations: it over-relies on macro-level analyses, insufficiently examines micro-level mechanisms, and inadequately considers heterogeneity. To address these gaps, this study empirically investigates the impact of export technological sophistication on corporate carbon emissions at the micro level, using data from Chinese A-share listed companies for the period 2013–2022. This study makes three key contributions. First, it shifts the research focus from the industry to the firm level, thereby addressing the scarcity of micro-empirical evidence. Second, it examines the underlying mechanisms—namely, R&D investment, financing constraints, and green total factor productivity—to elucidate how export technological sophistication affects carbon emissions. Third, it examines heterogeneity across ownership type, industry characteristics, and firm size, which uncovers differential effects and informs the design of more targeted environmental and economic policies globally. Theoretically, this study bridges a critical gap in the literature, which has predominantly focused on macro-level analysis at the expense of micro-level investigation, by uncovering the underlying mechanisms through which export technological sophistication influences corporate carbon emissions. Practically, the findings not only contribute to China's "Dual Carbon" goals (carbon peak and carbon neutrality) but also provide actionable insights for countries worldwide seeking to foster enterprises that can successfully balance technological competitiveness with environmental sustainability.

Existing research suggests that in high-tech industries, where technological innovation is particularly active, the effect of export technological complexity on reducing carbon emissions is more pronounced (Wang et al., 2017). Moreover, the more developed the market, the stronger the suppressive effect of export technological complexity on carbon emissions. Overall, the carbon reduction effect of export technological complexity intensifies with the level of industry technology intensity (Shahzad et al., 2020; Dong et al., 2023; Avenyo and Tregenna, 2022). These findings provide critical insights into how export technological complexity influences carbon emissions. Integrating the aforementioned theories and literature, we propose the following core hypothesis:

H1: A higher level of a firm's export technological complexity leads to significantly lower carbon emissions.

2.2. Mediating Mechanism Hypothesis: The Transmission Role of R&D Investment, Financing Constraints, and Green Total Factor Productivity

To further explore the underlying mechanisms through which export technological complexity influences carbon emissions, this study proposes and examines three mediating channels: R&D investment, financing constraints, and green total factor productivity. The rationale for each is as follows:

2.2.1. Mediating Role of R&D Investment

As global awareness of climate change intensifies, green industries have become a vital direction for China's economic development, a transition primarily driven by corporate technological innovation. This necessitates encouraging and guiding enterprises to increase R&D investment in green and low-carbon technologies. Enhancing export technological complexity is a key strategy for China to move into high-end global value chains and an important endogenous driver of its green transformation. The core mechanism operates as follows: increased export technological complexity incentivizes enterprises to boost R&D investment, thereby directing innovation resources toward technologies and processes that

reduce carbon emissions. Enterprises exporting products with high technological complexity face intense international competition. To maintain technological leadership, they must continuously invest in R&D to achieve technological iteration and product upgrades, necessitating sustained R&D expenditure. Furthermore, as they shift from labor-intensive to knowledge-intensive exports, they must also upgrade their production processes, technical standards, and quality control systems. This transition incentivizes firms to explore more energy- and resource-efficient production methods through R&D, reducing energy and material use per unit of output and laying the groundwork for carbon reduction. Consequently, R&D resources are prioritized for transforming traditional high-consumption, high-emission processes, which directly lowers carbon emissions. R&D investment is also channeled into more efficient end-of-pipe abatement technologies and the exploration of clean alternatives to achieve carbon reduction at the source. In summary, export technological complexity indirectly contributes to carbon reduction goals by stimulating R&D investment, reflecting the inherent logic of synergistic economic and environmental development. Therefore, we propose:

H2: R&D investment mediates the relationship between export technological complexity and carbon emissions. Specifically, enhanced export technological complexity reduces carbon emissions by increasing R&D investment.

2.2.2. The Mediating Role of Financing Constraints

China's economy is currently at a critical stage of transitioning toward a high-quality growth model. In this context, local governments are actively implementing policies to alleviate corporate financing constraints, thereby fostering coordinated policy efforts to advance this development goal. Thus, easing corporate financing constraints and supporting exports of high-tech, high-quality products have become key policy priorities for achieving coordinated progress in both high-quality development and China's "Dual Carbon" goals. Financing constraints, a key bottleneck hindering corporate green transformation, are closely tied to the enhancement of export technological complexity. By exporting high-tech products, enterprises can signal their technological capability and creditworthiness to the market, which effectively reduces information asymmetry for financial institutions and directly improves their access to financing. With eased financing constraints, enterprises can allocate more resources to low-carbon technological innovation. This enables them to directly enhance energy efficiency and optimize production processes through equipment upgrades, ultimately achieving significant reductions in carbon emissions. Consequently, the alleviation of financing constraints helps to reduce corporate carbon emissions. In other words, enhancing export technological complexity facilitates carbon reduction by alleviating the financing constraints faced by enterprises. This market-driven improvement in the financing environment not only helps enterprises overcome capital bottlenecks but also strengthens their incentives for green innovation, ultimately contributing to carbon reduction. This mechanism provides a novel theoretical lens for understanding how export technological complexity influences corporate carbon emissions. In summary, we propose:

H3: Financing constraints mediate the relationship between export technological complexity and carbon emissions. Specifically, enhanced export technological complexity reduces carbon emissions by alleviating financing constraints.

2.2.3. The Mediating Role of Green Total Factor Productivity

To foster synergy between green, low-carbon development and industrial upgrading, the government is pursuing a comprehensive green transformation in line with the "Dual Carbon" goals. By optimizing customs procedures and enhancing the green trade service system, it has created a conducive policy environment for enterprises to enhance both export technological complexity and green total factor productivity. As a core indicator that integrates technological progress and environmental constraints into a unified analytical framework, green total factor

productivity (GTFP) is a key metric for measuring the efficiency of green economic development. By synthesizing resource allocation efficiency, technological innovation, and environmental benefits, this indicator effectively captures the decoupling between economic growth and carbon emissions. Theoretically, increased export technological complexity signifies a shift toward high-value-added, technology-intensive products. This transformation drives GTFP growth through multiple pathways, effectively curbing carbon emissions. First, stringent international environmental standards and technological competition pressure enterprises to engage in green technology innovation. Such innovation directly enhances energy and material efficiency while continuously lowering the carbon footprint of entire production systems. Second, upgrading the export structure drives the reallocation of production factors from high-polluting, energy-intensive sectors to cleaner, more efficient industries. This resource reallocation, in turn, provides critical support for green technological innovation. Furthermore, economies with high export technological complexity are more likely to achieve decoupling between economic growth and carbon emissions—maintaining stable or even declining total carbon emissions while sustaining economic expansion. This pathway not only reveals the underlying mechanism through which export technological complexity influences carbon emissions but also has important policy implications for advancing green and low-carbon development. In summary, we propose:

H4: Green total factor productivity mediates the relationship between export technological complexity and carbon emissions. Specifically, enhanced export technological complexity reduces carbon emissions by improving green total factor productivity.

3. Research Design

3.1. Model Specification

3.1.1. Baseline Model

To examine the impact of export technological complexity on carbon emissions, we employ the following two-way fixed effects model (Eq.(1)):

$$Carbon_{it} = \alpha_0 + \alpha_1 EXPY_{it} + \alpha_2 X_{it} + \gamma_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Where $Carbon_{it}$ denotes the carbon emissions of firm i in year t , $EXPY_{it}$ denotes the export technological complexity of firm i in year t , X_{it} is the control variable, α_0 is the constant term, α_1 and α_2 are the parameters to be estimated, γ_i and λ_t represent the firm and year fixed effects, respectively, and ε_{it} represents the random error term.

3.1.2. Mediating Effect Model

Based on the preceding discussion of underlying mechanisms and the relevant literature, we hypothesize that export technological complexity reduces carbon emissions through three channels: increasing R&D investment, alleviating financing constraints, and enhancing green total factor productivity. To test this, we employ the two-step mediation approach established by Jiang (2022) to examine how export technological complexity affects carbon emissions. Specifically:

Step 1: Examine the effects of export technological complexity on R&D investment, financing constraints, and green total factor productivity (Eq.(2)).

$$M_{it} = \beta_0 + \beta_1 EXPY_{it} + \beta_2 X_{it} + \gamma_i + \lambda_t + \varepsilon_{it} \quad (2)$$

Step 2: Examine the effects of R&D investment, financing constraints, and green total factor productivity on corporate carbon emissions (Eq.(3)).

$$Carbon_{it} = \rho_0 + \rho_1 M_{it} + \rho_2 EXPY_{it} + \rho_3 X_{it} + \gamma_i + \lambda_t + \varepsilon_{it} \quad (3)$$

In Equations(2) and (3), M_{it} represents the mediating variables, including R&D investment (RD), financing constraints (SA_abs), and green total factor productivity (GTFP). and β_0 and ρ_0 denote the constant terms. β_1 is the estimated coefficient of the core explanatory variable on the mediating variable, ρ_1 is the estimated coefficient of the mediating variable on the dependent variable. and β_2 and ρ_3 are the parameters to be estimated. Other variables are interpreted as in equation(1).

3.2. Variable Descriptions

3.2.1. Dependent Variable (Carbon)

The dependent variable selected for this study is corporate carbon emissions. Calculations follow the methodology of Shen and Huang (2019), which determines the carbon emissions of firm i in year t by multiplying the proportion of the firm's primary business costs relative to the manufacturing sector's total primary costs by the total energy consumption, then by the carbon dioxide factor. This yields the following equation (Eq.(4)):

$$\begin{aligned} & \text{carbon dioxide emissions} \\ &= \frac{\text{main operating cost of enterprise}}{\text{main cost of industry}} \\ & \times \text{total energy consumption of industry} \\ & \times \text{carbon dioxide conversion factor} \end{aligned} \quad (4)$$

3.2.2. Explanatory Variable (EXPY)

The explanatory variable in this paper is the export technological complexity of enterprises. Drawing on the measurement methods of Hausmann et al. (2007) and Yu et al. (2018). we calculate the export technological complexity of Chinese enterprises.

First, we measure the export technological complexity of specific products (Eq.(5)):

$$PRODY_q = \sum_c \frac{x_{cq}/X_c}{\sum_c x_{cq}/X_c} pcgdp_c \quad (5)$$

where q denotes a product identified by the HS96 code, and c represents a country or region, x_{cq} is the export value of products q from country/region c, X_c is the total export value of country/region c, and $pcgdp_c$ is the per capita GDP level of country/region c.

Second, following Zhou (2006), the HS96 codes are converted to two-digit codes based on the National Economic Industry Classification. Then, the export product technical complexity at the industry level is calculated using the following formula (Eq.(6)):

$$EXPY_{cj} = \sum_q \frac{x_{jq}}{X_{cj}} PRODY_q \quad (6)$$

Where, x_{jq}/X_{cj} represents the share of country c industry j product q exports in the total exports of country c industry j.

Finally, following the approach of Gao and Yuan (2020), we adjust the industry export technical complexity using total factor productivity to derive the enterprise export technical complexity. The calculation formula is (Eq.(7)):

$$EXPY_i = \frac{TFP_i}{TFP_j} EXPY_{cj} \quad (7)$$

where $EXPY_i$ represents the enterprise i export technological complexity, and total factor productivity (TFP) is calculated using the method proposed by Lu and Lian (2012). Calculated by the LP formula, TFP_i denotes the enterprise's total factor productivity, and TFP_j denotes the industry's total factor productivity.

3.2.3. Control Variables

Beyond explanatory variables, other factors also influence corporate carbon emissions. Based on existing research by Tang et al. (2022); Liu et al. (2023); Zhou et al. (2022), the control variables selected for this study are: Debt-to-Asset Ratio (Lev), measured as the ratio of total liabilities to total assets; Net Profit Margin on Total Assets (ROA), expressed as the ratio of net profit to total assets; Cash Flow Ratio ($Cashflow$), calculated as the ratio of net cash flow from operating activities to total assets at year-end; Revenue Growth Rate ($Growth$), measured as the ratio of the difference between current-period revenue and prior-period revenue to prior-period revenue. Dual roles ($Dual$), 1 if the chairman and general manager are the same person, 0 otherwise. The largest shareholder's holding ratio ($Top1$) represents equity concentration, expressed as one hundredth. The company's years in operation (Age) is measured by the natural logarithm of the difference between the year of the year and the year of the enterprise opening plus one.

3.2.4. Mediating Variables

The mediating variables selected in this study are R&D investment, financing constraints, and green total factor productivity.

① R&D Investment (RD). The intensity of corporate R&D investment in innovation is measured by the ratio of R&D investment to operating revenue;

② Financing Constraints (SA_{abs}). Following the measurement methods of Hadlock and Pierce (2010); Ju et al. (2013), the SA index is used to measure corporate financing constraints. This study employs the absolute value of the SA index as an indicator of the degree of financing constraints (Eq.(8)).

$$SA = -0.737 * Size + 0.043 * Size^2 - 0.040 * Age \quad (8)$$

where $Size$ represents the natural logarithm of the firm's total asset size; Age denotes the firm's operating year, measured as the difference between the current observation year and the firm's founding year.

③ Green total factor productivity (GTFP). This study employs a non-radial SBM-ML model to calculate green total factor productivity, incorporating environmental pollution as an undesirable output into the efficiency measurement framework. This model simultaneously captures slack in multiple inputs and outputs, enabling an effective measurement of overall efficiency under resource and environmental constraints. Compared to traditional radial models, the SBM-ML approach more accurately reflects the actual performance of green development.

3.2.5. Data Sources and Explanation

Given data availability, this study utilizes data from Chinese A-share listed companies covering the period from 2013 to 2022. The cost of goods sold (COGS) for listed enterprises is sourced from the Guotai An (CSMAR) database; industry-level primary operating costs are derived from the Statistical Yearbook of China's Industrial Economy; total industry energy consumption data were obtained from the China Energy Statistical Yearbook; export technological complexity data primarily were obtained from the General Administration of Customs and the National Economic Industry Classification; data for control variables were obtained from CSMAR, corporate annual reports, the China Urban Statistical Yearbook, the China Environmental Statistical Yearbook, and corporate social responsibility reports.

Table 1. Variable Definitions and Measurements

Category	Name	Sign	Definition
Dependent Variable	Enterprise carbon emissions	Carbon	The calculation method is shown in formula (4)
Explanatory Variable	Enterprise export technological complexity	EXPY	calculated using the LP method
Control Variables	Debt-to-Asset Ratio	Lev	total liabilities / total assets
	Net Profit Margin on Total Assets	ROA	net profit / total assets
	Cash Flow Ratio	Cashflow	net cash flow / total assets at year-end
	Revenue Growth Rate	Growth	The difference between current-period revenue and prior-period revenue / prior-period revenue
	Dual roles	Dual	The chairman and general manager are the same person: 1. Otherwise: 0.
	The largest shareholder's holding ratio	Top1	The equity concentration ratio is 1/100.
	The company's years in operation	Age	$\ln(\text{current year} - \text{establishment year} + 1)$
Mediating Variables	R&D Investment	RD	R&D investment / operating revenue
	Financing Constraints	SA_abs	$SA_abs = -0.737 \times \text{Size} + 0.043 \times \text{Size}^2 - 0.040 \times \text{Age} $
	Green Total Factor Productivity	GTFP	Employing a non-radial SBM-ML model to calculate

4. Empirical Results Analysis

4.1. Baseline Regression

The baseline regression results are presented in Table 2. Column (1) reports the results without control variables, while Column (2) reports the results after incorporating the full set of control variables. The results indicate that the coefficients on export technological complexity (EXPY) are negative and statistically significant at the 1% level in both specifications. This suggests that a higher level of export technological complexity significantly reduces corporate carbon emissions—that is, the greater the export technological complexity, the lower the carbon emissions. This finding confirms the critical role of export technological complexity in corporate low-carbon transformation. Furthermore, the absolute value of the EXPY coefficient increases after including control variables, suggesting the presence of omitted variable bias in the model without controls, which underestimated the emission-reducing effect. Controlling for these variables mitigates this bias, allowing the suppressive effect of the core explanatory

variable to be more accurately estimated. These regression results provide initial empirical support for Hypothesis H1.

Table 2. Baseline Regression Results

Variables	(1)	(2)
	Carbon	Carbon
EXPY	-0.2743*** (0.0953)	-0.3289*** (0.0916)
Lev		-0.9436 (5.1019)
ROA		11.2223* (5.9304)
Cashflow		11.6401** (4.9866)
Age		-7.4412*** (1.8474)
Top1		32.7388 (35.0162)
Dual		1.9970* (1.1471)
Growth		0.1423 (0.0869)
Constant	24.2639*** (4.4751)	20.3426 (15.9042)
Enterprise FE	Yes	Yes
Year FE	Yes	Yes
Observations	20,726	20,726
R-squared	0.0357	0.0437

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. The values in parentheses represent robust standard errors, as do those in subsequent instances.

4.2. Robustness Tests

Table 3. Robustness Checks

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Change the sample range		Changing the measurement method of the dependent variable		Add control variables		Tail trimming	
EXPY	-0.3137*** (0.0962)	-0.3489*** (0.0912)	-0.0046** (0.0018)	-0.0065*** (0.0018)	-0.2743*** (0.0953)	-0.3548*** (0.0895)	-0.1651*** (0.0306)	-0.1807*** (0.0307)
Constant	28.1510*** (4.5072)	21.9493 (19.5927)	1.9375*** (0.0833)	1.6381*** (0.1027)	24.2639*** (4.4751)	8.6004 (13.8763)	12.4745*** (1.2894)	9.3302*** (1.6684)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16,227	16,227	20,726	20,726	20,726	20,726	18,654	18,654
R-squared	0.0335	0.0422	0.2331	0.2696	0.0357	0.0446	0.1901	0.2017

To ensure the robustness of our findings, we performed a series of robustness checks. First, we excluded sample data from the COVID-19 pandemic period (2019–2020) to minimize the confounding influence of this exogenous shock. Second, we redefined the dependent variable. Following the approach of Lei et al. (2023), we used the natural logarithm of (corporate carbon

emissions plus one) as an alternative proxy in the regression analysis. Third, we further controlled for additional key variables to address potential omitted variable bias. Finally, all continuous variables were winsorized at the 1st and 99th percentiles to mitigate the influence of extreme values on the estimation results. The results of these robustness tests, presented in Table 3, are consistent with the baseline regression findings, confirming the negative impact of export technological complexity on carbon emissions.

4.3. Endogeneity Test

This study employs an instrumental variable (IV) approach to address potential endogeneity arising from omitted variables, measurement errors, and reverse causality. Specifically, we use the one-period lagged value of a firm's export technological complexity as the instrument and estimate a two-stage least squares (2SLS) model. We argue that this instrument is plausibly exogenous, as it is correlated with the current export technological complexity but unlikely to directly affect current carbon emissions, thereby satisfying the exclusion restriction. The first-stage results (Column (1) of Table 4) confirm a strong positive correlation between the instrument and the endogenous variable at the 1% level, thus satisfying the relevance condition. The Kleibergen-Paap *LM* statistic rejects the null of underidentification ($p < 0.01$), and the Cragg-Donald Wald F-statistic of 2,843.68 far exceeds the Stock-Yogo critical value, ruling out concerns about weak instruments. The second-stage results (Column (2)) show that the coefficient on export technological complexity remains negative and statistically significant at the 1% level, confirming the robustness of our core finding to endogeneity concerns.

Table 4. Endogeneity Test

Variables	(1)	(2)
	EXPY	Carbon
L.EXPY	0.5215*** (53.3246)	
EXPY		-0.7922*** (-5.5753)
LM statistic	318.990***	
Wald F	2843.684 [16.38]	
Constant	21.7130*** (38.3685)	
Control variables	Yes	Yes
Enterprise FE	Yes	Yes
Year FE	Yes	Yes
Observations	16,838	16,838
R-squared	0.905	0.008

Note: Values in square brackets indicate P-values.

4.4. Mechanism Test

The regression results above consistently indicate that enhancing enterprise export technological complexity can effectively reduce carbon emissions. This paper further explores the underlying mechanisms at play.

4.4.1. R&D Investment

We posit that export technological complexity, entailing multidimensional technological upgrades and product innovation, can enhance corporate carbon performance by improving production and resource utilization efficiency. To test this mechanism, we measure innovation

intensity by the ratio of R&D expenditure to operating revenue (RD) and use it as the mediating variable. The results, presented in Columns (1) and (2) of Table 5, support this channel. Column (1) shows that higher export technological complexity significantly promotes R&D investment. Column (2) indicates that export technological complexity reduces corporate carbon emissions through increased R&D expenditure, evidencing a significant mediating effect. Therefore, Hypothesis H2 is supported.

4.4.2. Financing Constraints

Following Hadlock and Pierce (2010), this study employs the absolute value of the SA Index (*SA_abs*) to measure financing constraints and uses it as a mediating variable in the mechanism test. The SA index, based on firm size and age, reflects financing constraints by gauging the adequacy of internal cash flows to meet investment needs. We argue that improvements in export technological complexity can mitigate such constraints by enhancing capital efficiency and alleviating cash flow bottlenecks. This establishes a clear theoretical basis for testing the mediating role of financing constraints in the link between export technological complexity and carbon emission reduction. The results of the mechanism test are presented in columns (3) and (4) of Table 5. Column (3) shows that higher export technological complexity significantly alleviates financing constraints, as reflected by a lower *SA_abs* value. Column (4) indicates that export technological complexity significantly reduces corporate carbon emissions through this channel of alleviated financing constraints. Thus, Hypothesis H3 is supported.

4.4.3. Green Total Factor Productivity

Table 5. Mechanism Test Results

Variables	R&D Investment		Financing Constraints		Green Total Factor Productivity	
	RD	Carbon	SA_abs	Carbon	GTFP	Carbon
	(1)	(2)	(3)	(4)	(5)	(6)
EXPY	0.0002* (0.0001)		-0.0160*** (0.0011)		0.0040*** (0.0004)	
RD		-41.9550*** (15.0060)				
SA_abs				7.3881** (3.1605)		
GTFP						-2.8200** (1.0983)
Constant	0.0444*** (0.0050)	6.3210 (14.2818)	4.1999*** (0.0553)	-19.7478* (11.1747)	0.2011*** (0.0234)	7.2304 (14.1573)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	20,648	20,648	20,726	20,726	20,726	20,726
R-squared	0.1061	0.0446	0.3746	0.0448	0.4470	0.0431

Green total factor productivity represents a green extension of total factor productivity. Building upon conventional economic input-output frameworks, it incorporates constraints such as resource consumption, energy usage, and environmental pollution to comprehensively evaluate the coordinated efficiency of economic growth and environmental benefits. This paper references the research methodology of Guo and Liu (2023) to further explore the mediating role of green TFP. By integrating technological innovation and resource allocation efficiency improvements, green TFP transforms the structural upgrading driven by export technological complexity into low-carbon enhancements within the production system, thereby establishing

a critical bridge between economic growth and carbon emissions. Empirical results are presented in Table 5. Column (5) shows that the coefficient of export technological complexity on green TFP is significantly positive at the 1% level, indicating that increased export technological complexity significantly promotes green TFP growth. Column (6) reveals that the coefficient of green total factor productivity on carbon emissions is significantly negative at the 1% level, suggesting that improved green total factor productivity can drive corporate carbon reduction. This result, following the mediation test procedure, supports Hypothesis H4.

4.5. Heterogeneity Analysis

To further validate the differentiated impact of export technological complexity on carbon emission reductions across varying firm characteristics, this study conducts grouped regression analyses across three dimensions: ownership structure, industry sector (manufacturing vs non-manufacturing), and firm size. By integrating theoretical logic with empirical findings, it reveals patterns of heterogeneity, thereby providing a basis for tailored policy formulation.

4.5.1. Heterogeneity of Property Rights Nature

Systemic differences in environmental responsibility constraints and resource acquisition capabilities among enterprises with varying nature of property rights may lead to significant divergence in the carbon emission mitigation effects of export technological complexity. Empirical results are presented in Table 6: Within the state-owned enterprise sample group, export technological complexity exhibits a statistically significant negative effect at the 1% level; Within state-owned enterprises, the carbon emission reduction effect of increased export technological complexity is more pronounced, aligning with their inherent responsibility attributes and resource acquisition capabilities. On one hand, under the dual carbon goals, state-owned enterprises-as key pillars of the national economy-bear stronger environmental and social responsibilities. Their intrinsic motivation to reduce carbon emissions and drive green transformation, along with their willingness to implement policies, significantly exceeds that of non-state-owned enterprises (Zhang and Yu, 2025; Wang and Yang, 2025).

On the other hand, state-owned enterprises (SOEs) capitalize on their inherent political connections to gain preferential access to green policy support (e.g., green credit, R&D subsidies) and scarce resources (e.g., clean technology funding, carbon emission quotas). This advantage enables them to more effectively convert increased export technological complexity into emission reduction investments-such as optimizing production processes for high-value-added products and adopting low-carbon production technologies-thereby establishing a virtuous cycle of "technological upgrading → emission reduction and efficiency gains" (Zhang and Yu, 2025).

4.5.2. Industry-Specific Heterogeneity

Given the fundamental differences in energy consumption bases and technological pathways across industries, the mechanism through which export technological complexity influences carbon emissions exhibits distinct industry characteristics. Empirical results are shown in Table 6: Within the manufacturing sample group, the regression coefficient for export technological complexity is significantly negative at the 1% statistical level. This indicates that only among manufacturing enterprises does increased export technological complexity significantly reduce carbon emissions, revealing a pronounced sector-specific nature of its emission reduction effect. The core reason lies in the carbon emission baseline characteristics and technological adaptability of the manufacturing sector. As the primary source of industrial carbon emissions (Lei et al., 2023), manufacturing exhibits significantly higher energy consumption and pollutant emission intensity during production compared to non-manufacturing sectors. Technological innovations driven by increased export technological

complexity-such as production efficiency optimization, clean technology substitution, and low-carbon supply chain transformation-yield greater marginal contributions to emissions reduction. Specifically, manufacturing enterprises can drive product transformation toward higher value-added and lower energy consumption by increasing export technological complexity. This includes reducing the use of high-carbon intermediate goods and optimizing production processes to lower carbon intensity per unit output. In contrast, non-manufacturing enterprises have a lower carbon emissions baseline, resulting in relatively limited reduction potential from increased export technological complexity (Li et al., 2025; Li and Fu, 2025).

4.5.3. Heterogeneity in Firm Size

Heterogeneity in firm size-manifested in technological iteration speed, resource constraints, and policy responsiveness-shapes differentiated pathways through which export technological complexity influences carbon emissions. Following the approach of Zhao and Hu (2024), we classify firms as large or small and medium-sized enterprises (SMEs) based on whether their total assets are above or below the sample mean, and then conduct a grouped regression analysis. The empirical results, presented in Table 6, show that the negative effect of export technological complexity on carbon emissions is statistically significant at the 1% level within the SME subsample. This indicates that the carbon reduction effect is more pronounced for SMEs upgrading their export technological complexity. This advantage stems from SMEs' greater agility in technological iteration and their superior responsiveness to policy incentives. Compared to large firms, SMEs achieve higher technological conversion efficiency when enhancing export technological complexity. Their streamlined organizational structures and flexible production processes facilitate the rapid application of new technologies (e.g., digital production, precision energy management) to emission reduction practices (Li and Peng, 2025). Concurrently, upgrades in export technological complexity allow SMEs to more readily access policy support. For instance, those qualifying as "specialized, refined, distinctive, and innovative" enterprises become eligible for targeted subsidies and VAT incentives. This creates a virtuous cycle: "export technological upgrading → access to policy resources → increased investment in emission reduction" that further amplifies their carbon reduction outcomes. In contrast, large enterprises, despite their resource advantages, often operate within more rigid production systems and face stronger path dependence in technological iteration. This leads to longer conversion cycles from export technological upgrades to tangible emission reductions (Hu and Qiu, 2025).

Table 6. Heterogeneity Analysis

Variables	(1)	(2)	(1)	(2)	(1)	(2)
	state-owned	Non-state-owned	manufacturing	non-manufacturing	Large-scale	Small and medium scale
EXPY	-0.1709*** (0.0660)	-0.3418 (0.3201)	-0.3380*** (0.0946)	-0.0865 (0.2874)	0.3523 (0.7528)	-0.2546*** (0.0500)
Constant	14.2002*** (4.3420)	-19.0516 (72.8255)	19.7939 (16.4672)	48.6583** (24.3711)	-27.9416 (105.1395)	15.4592*** (4.9109)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Enterprise FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	16,161	4,565	20,147	579	2,913	17,813
R-squared	0.0259	0.0771	0.0432	0.1791	0.1030	0.0545

5. Research Conclusion and Policy Recommendations

5.1. Research Conclusion

Using data from Chinese A-share listed companies spanning 2013-2022, this study empirically investigates the impact of export technological complexity on corporate carbon emissions at the firm level. Our findings demonstrate that higher export technological complexity significantly reduces carbon emissions. This core finding holds after a series of robustness checks and endogeneity treatment, underscoring the critical role of technological advancement in fostering low-carbon transformation. Our mechanism analysis identifies three pathways through which export technological complexity drives carbon emission reduction: boosting R&D investment, easing financing constraints, and improving green total factor productivity. Notably, eased financing constraints facilitate corporate green innovation, while enhanced green total factor productivity decouples economic growth from carbon emissions through optimized resource allocation and the adoption of green technologies. Heterogeneity analysis further shows that this emission-reducing effect is more pronounced in state-owned enterprises, manufacturing firms, and small and medium-sized enterprises (SMEs).

Although this study provides micro-level evidence on the environmental benefits of export technological complexity, it is subject to several limitations that suggest directions for future research. First, corporate carbon emissions are indirectly estimated; future research would benefit from incorporating actual energy consumption or carbon accounting data to improve measurement accuracy. Second, this study does not account for other potential moderating variables, such as corporate governance and policy interactions; subsequent studies could employ moderation models to explore these channels in depth. Furthermore, the research period largely precedes the strengthening of China's "Dual Carbon" policy framework; future work should examine how policies like carbon markets and green finance moderate the identified relationship. Lastly, the absence of an international comparative perspective should be addressed in future research. Follow-up studies could undertake cross-country comparisons to explore the commonalities and differences in this relationship across different institutional contexts.

In summary, this study demonstrates that export technological complexity plays a crucial role in bridging trade upgrading with green transformation. Future research should explore data refinement, methodological advances, and international comparisons to build a more systematic theoretical framework for global green trade and corporate low-carbon development.

5.2. Policy Recommendations

Based on empirical findings and considering the technological complexity of carbon emissions and actual emission profiles among Chinese enterprises, this paper proposes the following recommendations:

First, develop innovative financing mechanisms to address the financing constraints hindering corporate green transformation. An evaluation system for export technological complexity should be established and incorporated into banks' green credit approval processes. Firms with high technological complexity should be prioritized for financing support, provided with preferential interest rates, and granted access to fast-track approval channels. Second, create a dedicated green technology upgrade fund to support projects that simultaneously enhance export technological complexity and reduce carbon emissions. Utilize interest-subsidized loans and risk compensation mechanisms to lower corporate financing costs. Finally, foster innovation in carbon finance products. This can be achieved by exploring instruments such as financing secured against carbon emission allowances and issuing green bonds linked to export technological complexity, thereby diversifying funding channels for low-carbon technologies.

Secondly, enterprises should prioritize green total factor productivity to drive low-carbon transformation, with a specific focus on enhancing export technological complexity. They need to integrate this goal into their strategic objectives and reduce carbon emissions by optimizing their technological structures. First, guide enterprises in adopting and transitioning to clean energy. This involves phasing out high-energy-consumption and high-carbon-emission equipment and fostering low-carbon innovation in production processes. For instance, companies should introduce clean technologies, such as photovoltaic power generation and industrial waste heat recovery systems, at key emission stages to optimize their energy mix. Second, support enterprises in establishing product lifecycle carbon management mechanisms. They should utilize digital tools to track carbon footprints from raw material procurement through production, thereby fostering collaborative emission reductions across the entire supply chain. Finally, encourage enterprises to integrate the goal of enhancing export technological complexity with green design and green manufacturing. This will enable them to develop high-value-added, low-carbon products and strengthen their competitive edge in the global green market.

Third, develop differentiated technological complexity roadmaps, prioritizing support for the low-carbon transformation of manufacturing enterprises. Given that manufacturing hosts major carbon emitters, tailored approaches are essential for advancing technological and equipment upgrades. First, provide targeted subsidies and low-interest loans for equipment renewal in energy-intensive sectors such as steel and chemicals. This will help enterprises adopt advanced low-carbon processes and technologies to reduce their carbon intensity. Second, establish regional shared technology service platforms to provide SMEs with services such as low-carbon technology audits, energy efficiency assessments, and green certification, thereby lowering the costs of green transformation. For instance, set up Green Technology Transformation Demonstration Parks for manufacturing. These zones can be dedicated to developing and promoting generic low-carbon technologies, thereby addressing the specific technical bottlenecks faced by SMEs.

Fourth, refine policy incentive mechanisms to enhance targeted support for high-tech complexity and green enterprises. Governments should innovate policy tools to stimulate enterprises' intrinsic motivation for green innovation. First, offer tiered tax incentives-such as additional R&D expense deductions and VAT reductions-to enterprises with high export technological complexity and significant carbon reduction achievements. Second, optimize green finance supply by incorporating carbon reduction performance into credit assessment criteria, offering financing conveniences like green credit interest subsidies and carbon reduction support tools to eligible enterprises. Finally, implement differentiated regulatory policies. For enterprises continuously enhancing technological complexity while achieving carbon reduction targets, provide preferential treatment in environmental impact assessment approvals and emission quota allocations. This encourages higher-level technological R&D, thereby boosting corporate investment in technological innovation and accelerating the green transformation of all enterprises.

Acknowledgments

Funding Information: This study was supported by the National Natural Science Foundation of China (Grant No. 72263015) and the Jiangxi Provincial Association of Social Sciences (Grant No. 23JL05).

References

- [1] Li, R. L., & Wang, Z. (2024). Changes in international external demand and enterprise trade upgrading-based on the perspective of export technological complexity. *International Business*, 41–57.
- [2] Du, Q. Y., & Li, K. (2019). Empirical examination of the relationship between export technological complexity and economic growth. *Statistics & Decision*, 35, 139–142.
- [3] Tu, N. S., et al. (2023). Research on the impact of manufacturing export technical complexity on green total factor productivity. *China Business Market*, 37, 78–89.
- [4] Bao, X. Z. (2024). Research on the impact of export technological complexity on the green transformation of the manufacturing industry-an empirical analysis based on a nonlinear panel model. *Price: Theory & Practice*, 184–188+231.
- [5] Ma, F. (2024). Digital economy, global value chain integration, and export technological complexity. *Statistics & Decision*, 40, 138–143.
- [6] Wang, S., & Wang, H. R. (2022). Research on the strategies of healthy development of China's digital economy under the background of carbon peaking and carbon neutrality goals. *Contemporary Economic & Management*, 44, 11–16.
- [7] Li, X., & Tian, Q. (2023). How does usage of robot affect corporate carbon emissions?-Evidence from China's manufacturing sector. *Sustainability*, 15, 1198.
- [8] Zhang, L. T., & Yu, X. H. (2025). Research on the impact of new quality productivity on enterprises' carbon emission-the role of national big data comprehensive pilot zone. *Journal of Industrial Technology & Economics*, 44, 24–33.
- [9] Li, L. H., & Li, L. (2024). Digital transformation, green technology innovation and enterprise ESG performance. *Statistics & Decision*, 40, 161–166.
- [10] Burki, U., & Dahlstrom, R. (2017). Mediating effects of green innovations on interfirm cooperation. *Australasian Marketing Journal*, 25, 149–156.
- [11] Wang, X. J., et al. (2017). Transformation of export structure, upgrading of export sophistication and carbon emission from China's manufacturing-under the perspective of global value chain. *Industrial Economics Review*, 8, 5–17.
- [12] Wu, X. L., & Pan, A. (2018). Does the technique effect lower China's embodied carbon emissions in foreign trade? *Economic Survey*, 35, 58–65.
- [13] Li, Z. M., & Qian, Z. Q. (2021). Linking into global value chains, export technology upgrades and value-added carbon emission in manufacturing sectors: an empirical evidence from Zhejiang's manufacturing sectors. *Ecological Economics*, 37, 35–40.
- [14] Wang, S. H., et al. (2025). Digital economy, industrial technical complexity and industrial carbon emissions. *Statistics & Decision*, 41, 95–101.
- [15] Shahzad, U., et al. (2020). Export product diversification and CO2 emissions: contextual evidences from developing and developed economies. *Journal of Cleaner Production*, 276, 124146.
- [16] Dong, K. Y., et al. (2023). How do green product exports affect carbon emissions? Evidence from China. *Chinese Journal of Population, Resources and Environment*, 21, 43–51.
- [17] Avenyo, E. K., & Tregenna, F. (2022). Greening manufacturing: technology intensity and carbon dioxide emissions in developing countries. *Applied Energy*, 324, 119726.
- [18] Jiang, T. (2022). Mediating effects and moderating effects in causal inference. *China Industrial Economics*, 100–120.
- [19] Shen, H. T., & Huang, N. (2019). Will the carbon emission trading scheme improve firm value? *Finance & Trade Economics*, 40, 144–161.
- [20] Hausmann, R., et al. (2007). What you export matters. *Journal of Economic Growth*, 12, 1–25.
- [21] Yu, J. J., & Yu, D. S. (2018). Government subsidies, industrial competition and enterprises' export technological complexity. *Journal of Finance and Economics*, 44, 112–124.

- [22] Zhou, S. (2006). Impacts of trade liberalization on the elasticity of China's labor demand. *Journal of World Economics*, 31–40+95.
- [23] Gao, X., & Yuan, K. H. (2020). Measurement and evolution analysis of the level of Chinese enterprises' servitization of manufacturing. *Journal of Quantitative & Technical Economics*, 37, 3–22.
- [24] Lu, X. D., & Lian, Y. J. (2012). Estimates of total factor productivity for Chinese industrial enterprises: 1999–2007. *China Economic Quarterly*, 11, 541–558.
- [25] Tang, H. D., et al. (2022). Market performance in digital transformation: can digital M&As enhance manufacturing firm's market power? *Journal of Quantitative & Technical Economics*, 39, 90–110.
- [26] Liu, K. H., et al. (2023). Can market-oriented low-carbon policies promote enterprise exports-evidence from carbon emission trading policies. *Journal of International Trade*, 88–105.
- [27] Zhou, C. B., et al. (2022). Has the carbon trading pilot market improved enterprises' export green-sophistication in China? *Sustainability*, 14, 10113.
- [28] Hadlock, C. J., & Pierce, J. R. (2010). New evidence on measuring financial constraints: moving beyond the KZ index. *Review of Financial Studies*, 23, 1909–1940.
- [29] Ju, X. S., et al. (2013). Financing constraints, working capital management, and the sustainability of corporate innovation. *Economic Research Journal*, 48, 4–16.
- [30] Lei, Y. T., et al. (2023). Research on the total quota setting of China's manufacturing carbon emission trading market under the targets of carbon peak and carbon neutrality. *Price: Theory & Practice*, 185–190.
- [31] Guo, H. H., & Liu, X. M. (2023). Can digital rural development promote agricultural green total factor productivity by reducing resource element mismatch? *Ningxia Social Sciences*, 107–117.
- [32] Wang, X., & Yang, J. F. (2025). A study on the enabling effect of digital transformation of manufacturing enterprises on carbon emission reduction from the perspective of green dynamic capabilities. *Journal of Southeast University (Philosophy and Social Sciences)*, 27, 8–20.
- [33] Li, Y. S., et al. (2025). Integrating digital and real economy to empower green development: digital transformation of manufacturing industry and green trade. *Modern Finance and Economics-Journal of Tianjin University of Finance and Economics*, 41, 22–39.
- [34] Li, X. P., & Fu, Z. A. (2025). The impact of the embeddedness in the regional value chain of the Belt and Road on enterprises' export technological sophistication. *Research on Financial and Economic Issues*, 502, 87–101.
- [35] Zhao, L., & Hu, Z. Y. (2024). Research on the influence mechanism of data elements on total factor productivity of enterprises: crack the "data productivity paradox". *Business Management Journal*, 46, 5–72.
- [36] Li, J. L., & Peng, Q. Y. (2025). How do new quality productive forces drive low-carbon transition of firms. *Journal of Xi'an Jiaotong University (Social Sciences)*, 45, 1–12.
- [37] Hu, Q. J., & Qiu, X. (2025). Can supply chain digitalization enhance the technological complexity of Chinese export technologies?-Evidence from pilot projects on supply chain innovation and application. *Modern Management Science*, 352, 29–41.