

Global Value Chain Participation and Firm-Level Carbon Emissions: Evidence from China

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Abstract:

This study investigates the impact of firm-level participation in global value chains (GVCs) on carbon emissions, using panel data on Chinese A-share listed firms from 2009 to 2023. We construct firm-level measures of GVCs participation based on overseas revenue and export intensity, and combine them with manually collected carbon emission data. Employing several robustness checks, we find evidence that deeper GVC participation significantly increases firms' carbon emission intensity, supporting the pollution haven hypothesis. Mechanism analyses show that firms with higher expansion capacity experience a stronger emission-increasing effect, consistent with a scale-expansion channel. In contrast, technological innovation does not significantly attenuate the emission effects of GVC participation, suggesting that the environmental benefits of technology upgrading through GVCs have not yet been fully realized. Overall, the findings highlight the dominance of scale effects in shaping firms' environmental outcomes and point to the importance of enhancing green technology diffusion and value-chain upgrading.

Keywords: Global Value Chains, Carbon Emissions, Pollution Haven Hypothesis, Chinese Market

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1. Introduction

This study aims to examine the impact of Chinese listed firms' participation in Global Value Chains (GVCs) on their carbon emissions and to identify the underlying transmission mechanisms. With the rapid development of production, information, and communication technologies, GVCs have assumed an increasingly prominent role in international trade. Multinational corporations are progressively dispersing different stages of their supply chains across various countries (Amendolagine et al., 2019; Wang et al., 2023). The production process of goods is fragmented into multiple stages, each characterized by distinct value-adding capacities. These sequential and separable stages of value addition constitute the division of the product value chain (Wang et al., 2023).

GVCs present both opportunities and challenges to the world economy. Participation in GVCs is particularly crucial for developing countries, as it serves as a pathway to industrialization and enhanced production efficiency (Szymczak, 2024). Through GVC integration, developing countries can expand their economic scale (Mudambi and Puck, 2016), gain access to advanced technologies (Javorcik, 2004; Baldwin and Lopez-Gonzalez, 2015), acquire professional management experience (Antràs and Yeaple, 2014), and promote gender equality (WTO, 2023). However, the power asymmetry among GVCs participants critically affects the distribution of gains derived from globalized production (WTO, 2023). A central concern is whether dominant actors (i.e. developed countries) at the higher end of the value chain capture a disproportionate share of profits, while less advanced participants (i.e. developing countries) remain locked into low-end production stages, facing constrained opportunities for learning and technological spillovers (Pietrobelli et al., 2018). Meanwhile, less advanced participants in GVCs typically shoulder greater environmental burdens, such as elevated carbon emissions (Wang et al., 2023).

Two major theories explain the relationship between GVC participation and the environmental impact in developing countries: the "pollution haven" hypothesis and the "pollution halo" hypothesis. The "pollution haven" hypothesis indicates that polluting industries relocate from developed to developing countries via international

trade and foreign direct investment (Copeland and Taylor, 2004). Developing countries often occupy the lower tiers of GVCs, relying on natural resources, cheap labor, and other comparative advantages to participate in high-carbon-emitting, low-value-added stages such as raw material supply, processing, assembly, and the production of simple components (Liu et al., 2020; Wang et al., 2022b). While this participation aims to foster economic growth, it places significant strain on resources and the environment, creating a dilemma for developing countries between trade benefits and environmental degradation (Liu et al., 2018; Meng et al., 2018). Based on the BP Statistical Review of World Energy 2019, developing countries contributed over 60% of global CO₂ emissions in 2018, substantially surpassing the emissions of developed nations. Thus, GVCs participation may offer a fast track for industrialization in developing countries but also entails considerable environmental costs (Wang et al., 2023).

In contrast to the “pollution haven” hypothesis, the “pollution halo” hypothesis suggests that GVC participation facilitates the introduction of advanced technologies in developing countries, such as pollution control technologies, which can benefit the local environment. Given that technological innovation is critical for reducing pollutant emissions, GVCs facilitate the diffusion of cleaner technologies, which in turn can enhance environmental quality in developing countries (Liu et al., 2018; Sun et al., 2019).

For China, after joining the World Trade Organization (WTO) in 2001, the country leveraged its advantages in labor, land, and resources to establish itself as a central hub in global manufacturing (Peters et al., 2011). By specializing in labor-intensive industries, China became the world’s largest exporter of manufactured goods, earning the title of the “world factory” and profoundly reshaping the global economic landscape (Huang et al., 2024; Li and Branstetter, 2024). However, this deep integration into GVCs has introduced challenges, particularly concerning over-reliance on resource-intensive industries and low-cost labor, which exert considerable pressure on the environment and domestic resources. Within the framework of China’s “dual carbon” strategy, corporate carbon emissions have become a central policy focus. Therefore,

investigating the impact of Chinese firms' GVCs participation on carbon emissions holds significant theoretical and practical relevance. Our research not only contributes to understanding the environmental implications of globalization but also provides insights for policymaking aimed at fostering China's green transition and sustainable development.

Our study employs an empirical approach, utilizing data from Chinese listed firms to comprehensively examine the impact of firm-level GVCs participation on carbon emissions through regression analysis. Specifically, we construct proxy variables for GVCs participation, e.g. the share of overseas revenue and export revenue, and conduct panel regression analyses in conjunction with corporate carbon emission data. Then, we apply a mediation model to test the roles of expansion capacity and technological innovation in the relationship between GVCs participation and carbon emissions.

The findings of this study indicate that deeper participation in GVCs leads to a significant increase in firm-level carbon emissions. Regression results reveal that both GVCs indicators exhibit a statistically significant positive association with carbon intensity. This supports the pollution haven hypothesis, suggesting that deeper GVCs participation in China amplifies the scale effect, thereby raising carbon emissions. Further analysis based on scale-expansion channel demonstrates that firms with higher expansion capacity that engage more in GVCs experience a greater increase in carbon emissions. This result reinforces the pollution haven hypothesis that China remains locked in low-value-added segments of GVCs, where greater participation primarily enhances economic gains at the expense of environmental quality. Moreover, evidence drawn from technological innovation does not support the pollution halo hypothesis. We find that GVCs participation does not significantly reduce carbon emissions even among firms with higher levels of technological innovation, implying that Chinese firms do not substantially benefit from GVCs in terms of emission reduction through mastering advanced technologies. These findings remain robust after employing alternative measures of GVC participation and addressing potential endogeneity concerns.

Our study has two contributions. First, the existing literature has predominantly examined the relationship between GVCs participation and carbon emissions from a macro perspective. For example, Shi et al. (2022) analyzed how Belt and Road countries' involvement in GVCs influences carbon emissions at the national level. Zhong et al. (2021) investigated the impact of GVCs participation in 39 major economies on embodied carbon emissions in trade and discussed potential environmental governance policies for achieving emission reduction targets. Nevertheless, research focusing on firm-level GVCs participation and its environmental consequences remains limited (Gao et al., 2024). Our study contributes to this gap by utilizing manually collected firm-level carbon emission data to empirically analyze the relationship between GVCs participation and carbon emissions.

Second, the environmental impact of China's integration into GVCs remains subject to debate. According to the "pollution haven" hypothesis, GVCs have enabled China to leverage scale effects, driving economic growth at the cost of environmental degradation. In contrast, the "pollution halo" hypothesis posits that GVCs facilitate technology transfer, allowing China to upgrade its production processes and reduce pollution through technological advancement. This study provides empirical evidence in support of the "pollution haven" hypothesis. We argue that, despite ongoing efforts toward green transition, China continues to function as a pollution haven within GVCs, characterized by high-carbon-emitting and low value-added production activities.

The rest of this paper is organized as follows. Section 2 introduces the institutional background of China. Section 3 reviews both theoretical and empirical literature and develops hypotheses. Section 4 shows the methodology of our study, such as sample and data, variables measurement, and summary statistics. Section 5 reports empirical results including baseline analysis, robustness checks, mechanism, and heterogeneity tests. Finally, Section 6 concludes our study.

2. Institutional background

In terms of GVC participation patterns, China engages predominantly through the

export of final products, leveraging its comparative advantage in assembly processing (Meng et al., 2018). Although the direct production processes of some final products in which China holds a comparative advantage (e.g., textiles and electrical products) may not generate substantial emissions, these exports directly and indirectly embody a significant amount of high-carbon domestic intermediate inputs (such as electricity and chemicals). Consequently, domestic emissions arising from final goods trade account for a considerable share of the total emissions induced by China's gross exports (Liu et al., 2016). Generally, most developing countries tend to export a relatively high proportion of final products during the initial stages of their integration into GVCs. In contrast, developed countries often participate more in GVCs through the export of high-tech intermediate goods (Meng et al., 2018).

In China, over 30% of its carbon emissions are induced by foreign final demand, a share significantly higher than that of other major economies (Peters et al., 2011; Meng et al., 2018). It can be explained by two factors. First, following China's accession to the WTO, foreign final demand has played an increasingly significant role in driving both economic growth and the increase in carbon emissions, with the share of final goods in China's total exports being substantially higher than that in many developed countries (Peters et al., 2011). Second, China's CO₂ emission intensity is higher than that of most developed countries (Davis and Caldeira, 2010; Xing, 2016), resulting in the larger proportion of domestic emissions embedded in the production of final goods (Meng et al., 2018). Additionally, production aimed at satisfying domestic demand can also induce carbon emissions through bilateral trade flows in intermediates (Meng et al., 2018). For instance, producing automobiles in China to meet domestic final demand may require importing engines, which themselves might be manufactured using Chinese metal components and inducing carbon emissions. Therefore, the above emission routes illustrate how engagement in GVCs can elevate China's domestic carbon emissions through international trades.

3. Literature review and hypothesis development

3.1 Theories

3.1.1 Pollution haven hypothesis

The pollution haven hypothesis posits that a developing country's integration into GVCs will lead to an increase in its carbon emissions (Copeland and Taylor, 2004). This hypothesis is based on the assumption that, aside from exogenous differences in environmental regulations, all other factors across countries are identical. Hence, the production of pollution-intensive goods becomes less costly in countries with weaker environmental governance (Copeland and Taylor, 2004; Zugravu and Ben, 2008). Compared to developing countries, the costs associated with pollution are generally higher in developed countries because of their more stringent regulations and higher costs of labor and resources. Therefore, firms in developed economies are highly motivated to relocate their production activities to developing countries with lower environmental standards (Esmaili, 2023). As a result, developed countries reduce net domestic emissions by offshoring the production of pollution-intensive goods to developing countries, thereby sourcing the final goods via direct and indirect imports (Arce et al., 2012).

The validity of this hypothesis can be tested through the scale effect, as proposed by Grossman and Krueger (1991). This effect suggests that economic growth entails the extensive exploitation of natural resources to meet high-output demands, thereby compromising environmental sustainability. It implies that participation in GVCs accelerates economic activity in developing countries, which simultaneously intensifies energy consumption and exacerbates environmental pollution (Cole and Elliott, 2003). Therefore, GVCs integration and carbon emissions can exhibit a positive linear relationship in developing countries based on the pollution haven hypothesis.

3.1.2 Pollution halo hypothesis

In contrast, the pollution halo hypothesis argues that a developing country's deeper integration into GVCs contributes to lower carbon emission levels. This hypothesis can

be explained by Grossman and Krueger (1991)'s technical effect, which implies that GVCs integration can facilitate technology transfer. Technological innovation serves as a critical pathway for firms to enhance their competitiveness and achieve sustainable development, while GVCs provide a conducive environment for the introduction and advancement of such technologies (Fagerberg, 2005; Aldy and Pizer, 2015). From the demand side, lead firms transfer stringent quality and environmental protection requirements to original equipment manufacturers, encouraging them to learn and catch up with green technologies from developed countries, thereby increasing production value-added and reducing embodied emissions (Liu et al., 2018). From the supply side, developing countries within GVCs can learn from multinational enterprises, enabling the transfer and spillover of clean technologies, which contributes to energy conservation and pollution reduction (Wang et al., 2019). Technological progress can effectively mitigate the scale effect (Abbasi et al., 2023). Hence, firms with deeper GVC integration are better positioned to leverage technological innovation for green transformation, leading to reduced carbon emissions (Wang et al., 2021).

3.2 Empirical literature

Over recent decades, a substantial body of research has provided evidence supporting the pollution haven hypothesis. For example, Kellenberg (2009), investigating the underlying drivers of outsourcing U.S. production processes to developing countries, concludes that a primary motivation for manufacturing relocation was significantly lower environmental stringency in those destinations (Xia et al., 2022; Bashir et al., 2020). Focusing on South and Latin American countries from 1980 to 2010, Sapkota and Bastola (2017) find that capital inflows from industrial economies can lead to environmental degradation in emerging markets. Further supporting this view, Peters et al. (2011) examine the link between global trade and carbon emissions, noting that China, as the world's manufacturing hub, saw its emissions rise by absorbing pollution-intensive production from developed nations. Similarly, Wei et al. (2024) observe that deeper participation by Chinese firms in GVCs led to a significant

increase in cross-border production and transportation activities, thereby elevating total carbon emissions.

Some studies, however, find more nuanced evidence that partly supports yet simultaneously challenges the pollution haven hypothesis. For instance, Cave and Blomquist (2008) report that the European Union increased imports of energy-intensive products from poorer countries during periods of stringent environmental regulation but did not increase imports of toxic-pollution goods. Kearsley and Riddel (2010) find no statistically significant relationship between greenhouse gas emissions and trade openness. While Cole (2004) validates the pollution haven hypothesis through empirical analysis of South-North trade data, he further argues that such effects were insufficient to cause serious long-term environmental deterioration. Based on a multi-regional input-output (MRIO) model, Wang et al. (2023) recalculate the emissions embodied in exports from developing countries and find an inverted U-shaped (nonlinear relationship) between the depth of GVCs integration and the carbon emissions of these countries. They argue that a low level of GVCs participation tends to hinder ecological improvement, whereas engagement beyond a certain threshold (i.e., exceed the inflection point) contributes to a reduction in embodied emission levels.

In contrast, some studies provide empirical evidence supports the pollution halo hypothesis. Dietzenbacher and Mukhopadhyay (2007), for example, argue that some developing countries, e.g. India, could benefit from GVCs integration through technology transfer and knowledge spillovers from developed economies. Liu et al., (2018) argue that participation in GVCs facilitates the exchange of technology and management expertise among multinational firms, encouraging the adoption of advanced production technologies and higher environmental standards. This, in turn, can enhance energy efficiency and reduce carbon emissions. Yang et al. (2022) suggest that GVC integration provides firms with access to leading international green technologies and management practices. Facing stricter environmental regulations in global markets, firms are incentivized to pursue technological innovation to lower carbon emissions in their production processes. Similar conclusions were drawn by

Asghari (2013) and Al-Mulali and Tang (2013) in their studies of developing countries in the Middle East, North Africa, and other regions.

3.3 Hypotheses development

Previous literature has provided evidence supporting both the “pollution haven” and the “pollution halo” hypotheses. Given that the scale effect supports the pollution haven hypothesis, while the technical effect explains the pollution halo hypothesis, which of these two effects dominates in different national contexts determines whether integration into GVCs has a positive or negative impact on a country’s carbon emissions. If the scale effect dominates, integration into GVCs is expected to generate a linear impact and may lead to increased carbon emissions; however, if the technical effect can offset the scale effect, such integration may instead be associated with a reduction in carbon emissions (Abbasi et al., 2023).

China, typically integrated into the global economy as an outsourcing destination, supplies final products to meet demand from developed countries (Meng et al., 2018). The positioning at the lower end of the value chain, defined by low value-added and high-carbon-emission activities, is often reinforced by dominant players within GVCs, making China susceptible to the low-end lock-in effect (Humphrey and Schmitz, 2002; Pietrobelli and Rabellotti, 2011; Wang et al., 2021). These resource- and labor-intensive production processes increase the embodied carbon emissions in international trade flows. Consequently, such lock-in adversely affects the local ecological environment, leading to persistent expansion in domestic pollution (Wang et al., 2023). To address these challenges, China is pursuing strategies to enhance resource efficiency and strengthen emission regulations (Song et al., 2019). In this context, deeper GVC participation could facilitate China’s comparative advantages and technological progress, thereby improving domestic energy environmental efficiency and reducing emissions (Vries and Ferrarini, 2017; Sun et al., 2019; Ye et al., 2020).

In sum, the literature has not reached a consensus on whether the scale effect or the technical effect dominates in the Chinese context. Therefore, we propose the

following competing hypotheses:

Hypothesis 1a: Participation in GVCs leads to an increase in carbon emissions at the firm level.

Hypothesis 1b: Participation in GVCs leads to a decrease in carbon emissions at the firm level.

4. Methodology

4.1 Sample and data

China first explicitly introduced the concept of participation GVCs after its accession to the WTO in 2001. This marked the beginning of China's deeper participation in the global economy and its emergence as an important link in GVCs. Since then, Chinese firms have accelerated their pace of integration into the global market. However, carbon emissions data at the firm level can only be traced back as far as 2008. Therefore, we choose all A-shared firms in the Shanghai and Shenzhen stock exchanges from 2009 to 2023. After removing missing value, the firm-year observations are 31,689.

In this study, our data are mainly obtained from CSMAR (China Securities Market and Accounting Research Database) and CNRDS (China Research Data Service Platform) databases, which are widely used in the Chinese financial market, covering multi-dimensional data such as listed firms' financial statements, shareholders' structure, and corporate governance.

4.2 Variables measurement

4.2.1 Global Value Chains

There are various approaches to measuring GVC participation, which can be broadly classified into macro-level and micro-level measures (Amador and Cabral, 2016; Kano et al., 2020). Macro-level measures typically rely on country-level input-output tables to capture the overall involvement of countries in global production

networks. A representative example is the Trade in Value Added (TiVA) approach proposed by Johnson and Noguera (2012), which traces value-added flows across countries by linking national input-output tables. This methodology provides a comprehensive and panoramic view of GVC structures and is particularly well suited for analyzing countries' forward and backward participation in GVCs.

Another widely used macro-level measure is vertical specialization, introduced by Hummels et al. (2001), which focuses on the cross-border flow of intermediate goods and the accumulation of value added along global production stages. Related measures, such as the direct import content of production, further assess countries' dependence on imported intermediates. While these macro-level indicators are valuable for understanding the aggregate structure of global production networks, they are less informative about firm-level behavior, as they abstract from heterogeneity across firms and cannot directly capture firms' strategic decisions or emission outcomes.

In contrast, micro-level measures focus on firm-level data and examine how individual firms are embedded in GVCs through their importing and exporting activities. The firm-level approach, as discussed by Koopman et al. (2014), allows researchers to identify firms' positions and roles within global production networks using detailed trade and financial information. Compared with macro-level measures, firm-level indicators are better suited to capturing heterogeneity in firms' participation patterns and to linking GVCs engagement with firm-specific outcomes.

Given that this study aims to examine the relationship between GVCs participation and firm-level carbon emissions, adopting a micro-level measurement approach is particularly appropriate. Specifically, we measure firms' GVCs embeddedness using two indicators. The first is the Overseas Income Ratio (GVC1), defined as the share of overseas business revenue in total revenue, which reflects a firm's reliance on international markets. The second is the Export Ratio (GVC2), defined as the proportion of export revenue in total revenue, capturing the depth of a firm's engagement in global trade.

These firm-level measures offer several advantages for the purpose of this study.

They allow us to directly link firms' GVCs participation to their emission performance, reduce aggregation bias inherent in macro-level measures, and capture dynamic and heterogeneous firm behaviors within GVCs. As a result, the adopted approach provides a more suitable empirical basis for analyzing how participation in global value chains affects environmental outcomes at the firm level.

4.2.2 Carbon emission

According to international standards, corporate carbon emissions can be categorized into three scopes: Scope 1 is direct carbon emissions that arise from sources owned or controlled by the firm; Scope 2 is indirect carbon emissions, which come from greenhouse gases generated by purchased electricity and heat consumed by the firm; and Scope 3 comprises other sporadic indirect emissions (Greenhouse Gas Protocol, 2015).¹

The difficulty in carbon emissions research is the availability of corporate carbon emissions data. For Chinese listed firms, Carbon emissions data mainly come from self-disclosure, including corporate social responsibility reports (known as CSR reports), sustainable development reports, or environmental reports. Scope 1 and 2 data have been more systematically reported and accurately estimated because scope 1 and 2 emissions are easier to measure and disclosure requirements are more stringent (Bolton and Kacperczyk, 2021). Scope 1 and 2 carbon emissions are mandatory disclosures required by the System of Greenhouse Gas Accounting (GHGAS), so the total carbon emissions commonly disclosed by firms refer to the sum of Scope 1 and Scope 2 emissions. To prepare for the collection of firm-level carbon emissions data, Scope 3 emissions are not considered in our study.

We followed the manual collection method of Wang et al. (2022a) to collect carbon emission data from listed firms based on firm disclosure. For firms that directly disclose their annual direct carbon emissions, indirect carbon emissions, or total carbon emissions, we directly use the data disclosed in their reports and standardize the units. For those firms without annual emissions disclosure, we calculate Scope 1 and Scope

¹ <https://ghgprotocol.org/corporate-standard> .

2 emissions separately based on the China Development and Reform Commission issued the “Guidelines on Accounting Methods and Reporting of Greenhouse Gas Emissions by Firms” for different industries and firms disclosed different types of fossil energy consumption, electricity consumption, and heat consumption. Finally, the total carbon emissions are the sum of Scope 1 and Scope 2 emissions.

4.3 Summary statistics

Table 1 demonstrates the distribution of data over time in the study sample. The purpose of the table is to show the distribution of the sample data between years to provide temporal contextual support for the analysis. The distribution of data from 2009 to 2022 shows a steady increase in the sample size, with a significant increase in 2021 and 2022. This reflects the expansion of GVCs over time, improved corporate disclosure, and increased availability of relevant data.

In 2016 and 2017, there was a relative decrease in the sample size, which may have been due to a reduction in business activity due to policy changes or industry volatility. These changes may be related to the global economic environment, domestic policy adjustments, or external market uncertainty.

[Insert Table 1 about here]

Table 2 reports the descriptive statistics for all key variables used in the analysis, including carbon emission intensity (*CE_Intensity*), global value chain participation (*GVC1* and *GVC2*), firm size, leverage, return on assets (*ROA*), firm age, ownership, and corporate governance characteristics.

The average value of carbon emission intensity is 13.31, with a substantial standard deviation of 13.19, suggesting pronounced variation in firms’ emission performance. Despite the existence of unified national emission standards, firms differ substantially in their emission efficiency, as reflected in the wide range between the minimum and maximum values (11.00 and 16.10). This heterogeneity highlights the uneven environmental performance across Chinese listed firms.

GVCs participation, measured by *GVC1* and *GVC2*, also exhibits significant dispersion. The mean values of 0.130 and 0.140 indicate that, on average, Chinese firms maintain relatively limited exposure to global markets. The wide distribution, ranging from near zero to 0.670, suggests substantial cross-firm differences in the extent of internationalization. This pattern is consistent with prior evidence that Chinese firms vary widely in their participation and depth of integration within global value chains.

Firm size has a mean of 22.23 (log-transformed), indicating that the sample consists predominantly of relatively large firms, while the dispersion (SD = 22.03) reflects notable variation across firms. Leverage has a low mean value (0.040), but the maximum reaches 0.220, implying that although most firms maintain conservative capital structures, some operate under significantly higher debt pressure. ROA displays meaningful variation as well, with a mean of 0.040 and a standard deviation of 0.040, reflecting differences in profitability that may influence firms' environmental and internationalization decisions.

[Insert Table 2 about here]

Table 3 demonstrates the correlations between the key variables in the study, helping us to understand the potential relationships between the variables and providing guidance for the multiple regression analyses. The correlations between the other control variables above 0.7 are not observable, indicating that the problem of multicollinearity is not present.

[Insert Table 3 about here]

5. Empirical results

5.1 Baseline analysis

In our baseline analysis, we examine the relationship between the firm's participation in GVCs and carbon emissions using the following OLS regression:

$$CE_Intensity_{i,t} = \beta_0 + \beta_1 GVC_{i,t} + Controls_{i,t} + \gamma_i + \delta_t + \varepsilon_{i,t},$$

where $CE_Intensity_{i,t}$ is a measure of the firm's carbon emission, scaled by its total revenue. In our baseline regressions, $GVC_{i,t}$ is our key independent variable of interest, and it has two measures: the proportion of overseas income and the proportion of export revenue. Our regression analysis controls for a set of firm-level characteristics following previous studies. We control corporate governance indicators, including board size (*Board size*), board independence (*Independent*), and board diversity (*Diversity*). We also include capital structure, an indicator of State-Owned Enterprises (*SOE*), and the proportion of shares of the largest shareholder (*Top1*). We control firms' financial indicators, including leverage (*Leverage*), return on total assets (*ROA*), market-to-book ratio (*MB*), the percentage of tangible assets (*Tangibility*), and the natural log of total assets (*Size*). We also control for firm age (*Age*), and the Herfindahl Hirschman Index (*HHI*), a comprehensive index used to measure industrial concentration. Finally, we control firm-fixed effects and year-fixed effects to account for unobserved firm and year heterogeneity. All control variables are defined in Appendix A.

Table 4 presents the baseline regression results testing hypothesis 1a, which posits that firms' participation in GVCs increases their carbon emission intensity. Across all specifications, the estimated coefficients on GVCs participation are positive and statistically significant, providing consistent empirical support for this hypothesis. This finding holds for both measures of GVCs engagement (*GVC1* and *GVC2*), indicating that deeper integration into global production networks is associated with higher firm-level carbon emission intensity.

Columns (1) and (2) report estimates without fixed effects and show a strong positive correlation between GVCs participation and emission intensity. Columns (3) and (4) incorporate firm and year fixed effects to control for unobserved time-invariant firm characteristics and common macroeconomic shocks. Although the coefficient magnitudes decline after the inclusion of fixed effects, they remain positive and

statistically significant, suggesting that the observed relationship is not driven by omitted firm-specific factors and reflects a within-firm effect over time.

The estimated coefficients are not only statistically significant but also economically meaningful. The results imply that firms participating more deeply in GVCs tend to expand production scale and operational intensity in response to global market linkages, thereby increasing carbon emission intensity. This pattern is consistent with the scale-effect mechanism emphasized by the pollution haven hypothesis and provides a foundation for the subsequent analysis of underlying channels.

Regarding the control variables, firm size, profitability, asset tangibility, board size, market concentration, and state ownership are positively associated with emission intensity, while leverage and market valuation are negatively related. Overall, these findings are in line with prior expectations and reinforce the robustness of the baseline results.

[Insert Table 4 about here]

5.2 Alternative models and measures

To ensure that the baseline results are not driven by model specification choices or by the specific definition of GVCs participation, we conduct a battery of robustness tests, summarized in Table 5.

Columns (1) and (2) introduce industry-by-year fixed effects, a highly stringent specification that absorbs all time-varying shocks common to firms within the same industry. After controlling for this rich set of fixed effects, the coefficients on *GVC1* and *GVC2* remain positive and statistically significant, indicating that the baseline relationship is not explained by industry-level dynamics such as technology adoption, regulatory shifts, or global sector-specific shocks.

Columns (3) and (4) incorporate lagged carbon emission intensity to account for the persistence of firms' environmental performance. The lagged dependent variable is positive and highly significant, consistent with strong temporal inertia in emission intensity. Importantly, the coefficients on *GVC1* and *GVC2* remain positive and

significant, demonstrating that the effect of GVCs participation is not an artifact of unobserved serial correlation or adjustment dynamics.

Columns (5) to (7) replace the primary GVCs indicators with three alternative measures. *GVC3*, defined as the number of overseas subsidiaries, captures firms' physical presence abroad. *GVC4* and *GVC5*, constructed based on alternative criteria (The number of overseas affiliated companies and the number of different countries and regions where the overseas subsidiaries are located), offer further proxy variations for firms' involvement in global value chains. Across all three alternative measures, the coefficients remain positive and statistically significant, reinforcing that the positive association between GVCs participation and carbon emission intensity is not sensitive to how GVCs engagement is operationalized.

[Insert Table 5 about here]

5.3 Endogeneity concerns

A key challenge in identifying the effect of GVCs participation on firms' carbon emission intensity is the potential endogeneity of GVCs involvement. Firms may self-select into GVCs based on unobserved productivity, managerial capability, or strategic decisions that are also correlated with their emission performance. Moreover, reverse causality is plausible: firms with the capacity to expand production or undertake international operations may simultaneously exhibit higher emissions and be more likely to participate in GVCs. These concerns imply that OLS estimates may suffer from both omitted variable bias and simultaneity bias. To address these identification issues, we adopt two complementary strategies: an instrumental variable (IV) approach and a difference-in-differences (DID) strategy based on exogenous policy variation.

5.3.1 Instrumental variable approach

To mitigate endogeneity concerns, we employ an IV strategy based on a shift-share design commonly used in empirical international trade and economic geography (e.g., Autor et al., 2013; Faber 2014; Head and Mayer, 2014; Hummels et al. 2014). The

instrument exploits exogenous variation created by the interaction between firms' predetermined geographic exposure to global trade routes and aggregate movements in world trade.

The firm-level exposure measure is constructed using the logarithmic distance between a firm's headquarter location and the nearest major seaport. This geographic characteristic is fixed over time and reflects historical settlement patterns rather than current economic choices, making it plausibly exogenous to firm-level environmental outcomes during the sample period.² Firms located closer to major ports are naturally more connected to international transportation networks and thus more sensitive to foreign demand shocks.

We interact this time-invariant exposure measure with the annual growth of global trade volume, which captures macroeconomic shocks determined outside the domestic economy.³ Since global trade fluctuations are driven by international economic conditions and geopolitical developments unrelated to any individual firm, they provide a source of exogenous temporal variation. The resulting interaction term, *GVC_ExposureIV*, generates exogenous variation across both the geographic and temporal dimensions, yielding a powerful and conceptually grounded instrument for GVCs participation.

This identification strategy aligns with a long tradition of using geographic frictions and external trade shocks to instrument for firms' global integration (Duranton et al., 2014; Eaton et al. 2016; Tang and Zhang, 2021). The exclusion restriction is also credible: while global trade growth may influence aggregate economic conditions, its differential impact across firms is mediated exclusively through their relative exposure determined by port proximity. In other words, conditional on firm and year fixed effects, the instrument affects carbon emission intensity only through its effect on firms' GVCs participation.

Table 6 reports the results from the first-stage and two-stage least squares (2SLS)

² We measured the straight-line distance between the firm's headquarter address and the nearest port using Amap, then took the logarithm.

³ We have selected the total volume of global merchandise exports, with data sourced from the WTO.

estimations. The first stage shows that the instrument strongly predicts both *GVC1* and *GVC2*, with Kleibergen-Paap rk Wald F statistics far exceeding conventional critical values. This suggests that weak-instrument concerns are minimal. The second-stage estimates indicate that instrumented GVCs participation has a positive and statistically significant impact on carbon emission intensity, with coefficients larger than the OLS estimates. This pattern is consistent with the presence of attenuation bias or negative selection into GVCs participation in the OLS results. Overall, the IV analysis provides robust evidence that GVCs participation causally increases firms' carbon emission intensity.

[Insert Table 6 About Here]

5.3.2 Difference-in-Differences (DID) approach

As a complementary strategy to the instrumental variable analysis, we implement a DID design that leverages the 2015 reform of China's export tax rebate system. Beginning in 2015, the central government assumed full responsibility for financing export rebate payments, replacing the previous cost-sharing arrangement between central and local governments. This reform represents an exogenous shock that altered the relative incentives for firms to expand export activities, particularly for those with pre-existing exposure to international markets. Because the reform was implemented nationwide and was unrelated to contemporaneous firm-level environmental performance, it provides a plausibly exogenous setting for identifying the effect of increased GVCs participation on carbon emission intensity.

To construct treatment and control groups, we classify firms based on their pre-reform overseas business involvement. Firms that engaged in foreign sales or maintained overseas operations prior to 2015 are designated as treated firms, whereas firms without any international activities serve as the control group. This definition captures heterogeneous sensitivity to the reform: firms already participating in cross-border activities are more likely to respond to a reduction in the effective cost of export

expansion, while firms focused exclusively on domestic markets remain largely unaffected. The DID estimator therefore identifies the differential change in carbon emission intensity following the reform between firms with high and low exposure to the export rebate adjustment.

Table 7 reports the baseline DID estimates. Column (1) shows that the coefficient on the interaction term, DiD , is positive and highly significant, indicating that the 2015 export rebate reform led to a disproportionate increase in carbon emission intensity among firms with pre-existing foreign activities. This result is consistent with the interpretation that the reform incentivized these firms to expand their global engagements, either through larger export volumes or deeper GVCs participation, which in turn contributed to higher emission intensity.

To further validate the design, we conduct a placebo test using 2013 as a fictitious policy year. Column (2) demonstrates that the placebo $DiD_{placebo}$ coefficient is statistically insignificant, reinforcing that the observed treatment effect in 2015 is unlikely to be driven by pre-existing differential trends or spurious correlations. Together, the baseline and placebo results support the credibility of the DID identification strategy.

[Insert Table 7 About Here]

5.4 Mechanism

To further understand why participation in GVCs increases firms' carbon emission intensity, this subsection examines two mechanisms rooted in firms' internal capacity to adjust production when expanding international operations. Prior literature suggests that the environmental consequences of globalization vary systematically across firms, depending on their cost structures and technological capabilities (Baldwin and Robert-Nicoud, 2014). Building on this insight, we investigate whether (i) firms' capacity or motivation to expand production and (ii) their level of digital capability shape the extent to which GVC participation amplifies emission intensity. These mechanisms reflect how different types of firms scale or transform their production processes when

integrating more deeply into global markets.

5.4.1 Expansion capacity channel

A growing body of GVC research shows that downstream lead firms play a central role in transmitting demand conditions and coordinating production across global supply networks (Antràs and Chor, 2013; Gereffi et al., 2005). When firms become more deeply integrated into GVCs, they are exposed to larger and more volatile external demand, making their environmental outcomes increasingly dependent on how strongly they scale production in response. In this setting, differences in financial flexibility and the stability of commercial relationships shape firms' capacity and willingness to expand output when international production opportunities arise.

To empirically examine this expansion-based mechanism, we use two firm-level indicators that capture distinct aspects of firms' ability or motivation to scale production. The first is the gross margin ratio, which reflects financial slack and operational flexibility. Firms with higher margins can accommodate rising GVC-related demand more easily by expanding capacity, thereby amplifying scale effects. The second indicator is customer stability, which measures the persistence of major customer relationships. Stable buyers reduce demand uncertainty and strengthen firms' incentives to expand output when participating more deeply in GVCs. Both variables therefore capture complementary channels through which GVC integration may lead firms to scale production more aggressively, with corresponding implications for carbon emissions.

Table 8 reports the results using these two proxies. The interaction terms $GVC1 \times Margin$ and $GVC2 \times Margin$ remain significantly positive across all specifications. Similarly, the interaction terms $GVC1 \times Customer_Stability$ and $GVC2 \times Customer_Stability$ also yield positive and statistically significant coefficients. Together, these findings indicate that the marginal emission-increasing effect of GVCs participation is more pronounced among firms with stronger pricing power or more stable customer relationships. These firms are better positioned to expand production

aggressively when integrated more deeply into GVCs, amplifying scale effects that dominate any efficiency gains associated with internationalization.

This result implies that firms with greater pricing power expand production more aggressively when entering or deepening GVCs activities, thereby increasing scale effects that outweigh any potential efficiency gains. This mechanism is consistent with the literature showing that firms with greater market power tend to exploit export opportunities more intensively (Melitz and Ottaviano 2008) and that performance-based expansion often leads to temporarily higher environmental footprints (Cole et al., 2010).

[Insert Table 8 About Here]

5.4.2 Technological innovation channel

A central argument of the pollution halo hypothesis is that participation in GVCs facilitates technology transfer and learning, enabling firms in developing economies to adopt cleaner production technologies and thereby reduce carbon emissions (Grossman and Krueger, 1991; Liu et al., 2018; Wang et al., 2019). Through closer interaction with multinational lead firms, suppliers are expected to benefit from knowledge spillovers, stricter environmental standards, and improved production processes, which together constitute the so-called technical effect of globalization (Aldy and Pizer, 2015; Fagerberg, 2005). If this mechanism operates effectively, firms with stronger innovation capabilities should be better positioned to internalize green technologies and mitigate the environmental costs associated with GVCs participation.

To empirically examine this channel, we test whether firm-level technological innovation moderates the relationship between GVCs participation and carbon emission intensity. Following the innovation and environmental economics literature, we employ two complementary proxies for technological capability. The first is R&D intensity, measured as R&D expenditure relative to operating revenue, which captures firms' innovation input and absorptive capacity (Cohen and Levinthal, 1990; Lileeva and Trefler, 2010). The second is the number of green patents, reflecting firms' output-

oriented achievements in environmentally related technologies and their capacity for green innovation (Aghion et al., 2016; Popp, 2002). We interact each innovation measure with our two indicators of GVCs participation (*GVC1* and *GVC2*) and estimate fixed-effects regressions controlling for firm and year heterogeneity. The results are reported in Table 9.

Contrary to the predictions of the pollution halo hypothesis, the interaction terms between GVCs participation and technological innovation are statistically insignificant across all specifications. Neither *GVC1* × *R&D ratio* (or *GVC2* × *R&D ratio*) nor *GVC1* × *green patent* (or *GVC2* × *green patent*) exhibits a significant negative coefficient. This indicates that firms with higher innovation intensity or stronger green patent portfolios do not experience a weaker emission-increasing effect from GVC participation. In other words, technological capability does not moderate the carbon costs associated with deeper integration into global value chains.

These findings are consistent with the low-end lock-in argument in the GVCs literature, which emphasizes that firms in developing countries often remain confined to production and assembly stages characterized by limited learning opportunities and weak technological spillovers (Humphrey and Schmitz, 2002; Pietrobelli and Rabellotti, 2011). Even when firms invest in R&D or generate green patents, such innovation activities may be incremental or process-oriented, rather than transformative enough to fundamentally alter energy use or production structures (Acemoglu et al., 2012; Wang et al., 2021). Moreover, lead firms in GVCs may restrict the diffusion of core green technologies to protect intellectual property, thereby limiting the environmental upgrading potential of supplier firms (Gereffi et al., 2005).

[Insert Table 9 About Here]

5.5 Heterogeneity tests

To further understand the heterogeneous environmental impacts of firms' participation in GVCs, we conduct a set of subgroup analyses along four economically meaningful firm characteristics: (i) competitive intensity, (ii) ownership type, (iii)

pollution attributes of the industry, and (iv) technological sophistication. These dimensions reflect structural differences in firms' operating environments and strategic constraints that the literature identifies as central determinants of their responses to globalization and environmental regulation (Aghion et al. 2005; Bloom et al. 2010; Brandt et al. 201; Chen et al., 2021; Yang et al., 2025). Table 10 summarizes the results.

Panel A compares firms operating in high-competition versus low-competition markets, where competition is measured using the industry-level Herfindahl-Hirschman Index (HHI). The results show that GVCs participation significantly increases carbon emission intensity only for firms in low-competition industries. This pattern is consistent with the view that in competitive industries, firms face more stringent cost pressures and narrower margins, which limit their ability to scale production aggressively in response to global opportunities (Melitz and Ottaviano 2008). By contrast, firms in less competitive markets enjoy greater market power and are better positioned to expand output when integrating into GVCs, resulting in a more pronounced scale-driven increase in emissions.

Panel B distinguishes between state-owned enterprises (SOEs) and non-SOEs. The results indicate that the positive association between GVCs participation and emission intensity is stronger among non-SOEs. This is consistent with prior evidence that SOEs tend to face softer budget constraints, stricter political oversight, and more explicit environmental compliance requirements (Li and Zhou, 2005; Yang et al., 2024). Non-SOEs, conversely, are more profit-driven and more responsive to foreign market incentives, leading to greater expansion of carbon-intensive production when joining GVCs.

Panel C compares high-pollution versus low-pollution industries, based on official classifications.⁴ The effect of GVCs participation is considerably more pronounced among high-pollution industries, which inherently depend more on energy-intensive processes. This aligns with findings in the environmental economics literature showing

⁴ We follow Ge et al. (2025) and Qiu et al. (2023) to define the high pollution industry. A total of 15 sectors are classified as high-pollution industries, including B06, B07, B08, B09, C17, C19, C22, C25, C26, C28, C29, C30, C31, C32, D44. Non-heavily polluting industries comprise B, C, D and all other sectors.

that firms in pollution-intensive sectors exhibit larger environmental externalities when responding to globalization shocks (Cole et al., 2010). The result highlights sectoral differences in technological substitutability between clean and carbon-intensive inputs.

Panel D evaluates heterogeneity across high-technology versus low-technology industries.⁵ The results show that the emission-increasing effect of GVCs participation is concentrated in high-technology industries. One plausible explanation is that technologically advanced firms are better equipped to coordinate complex international operations and absorb export demand shocks, creating a strong scale effect (Bustos, 2011; Lileeva and Trefler, 2010). Although high-tech firms may possess cleaner technologies, the expansionary response to GVCs integration dominates, resulting in higher emission intensity.

[Insert Table 10 about here]

6. Conclusion

This study empirically investigates the relationship between firm-level participation in GVCs and carbon emissions, using a sample of Chinese listed companies. By constructing proxy variables for GVCs integration, we examine both the direct environmental impact and the underlying mechanisms of firm's expansion capacity and technological innovation.

Our core findings demonstrate that deeper GVCs participation significantly increases firm-level carbon emissions. This positive association between GVCs indicators and carbon intensity provides strong empirical support for the "pollution haven" hypothesis in the Chinese context. The results suggest that China's current mode of GVCs integration predominantly amplifies the scale effect, wherein expanded production for global markets leads to higher emissions. Further mediation analysis reveals that firms with higher expansion capacity within GVCs are particularly susceptible to increased emissions, reinforcing the view that China remains structurally locked into low-value-added, high-carbon segments of global production. Notably, we

⁵ In accordance with the China Securities Regulatory Commission's 2012 classification guidelines for listed companies in China, we define companies with classification codes falling within C25-C29, C31-C32, C34-C41, I63-I65, and M73 as high-tech industry companies following the prior literature (e.g., Zhang et al., 2012).

find no supportive evidence for the “pollution halo” hypothesis; even technologically innovative firms do not achieve significant emission reductions through GVCs participation, indicating that the anticipated channels for clean technology transfer and spillover are not effectively operating for Chinese manufacturers.

These results carry important implications for regulators. First, policies should actively support Chinese firms in moving up the value chain from assembly and processing to higher value-added activities like design, and branding, thereby reducing reliance on carbon-intensive production stages. Second, domestic environmental regulations should be strengthened and better aligned with GVCs requirements. Incentives could be provided for “lead firms” to adopt and enforce green procurement standards, thereby creating market-driven pressure for supply-chain decarbonization. Third, while technology alone is insufficient, national innovation policies should be more strategically focused on mission-oriented green technologies (e.g., energy efficiency, carbon capture, circular economy solutions) and ensure that GVCs participation is leveraged explicitly to access and absorb these specific technologies.

Our research is also subject to several limitations. First, the exclusive focus on Chinese firms restricts the generalizability of the findings to other national contexts, as China’s unique institutional environment, industrial structure, and developmental trajectory may shape the GVC-emission nexus in ways not applicable elsewhere. Second, while we proxy GVCs participation using financial metrics, future research could incorporate more nuanced measures, such as position in the value chain (forward/backward participation) or the environmental intensity of imported intermediates. Third, our analysis focuses on carbon emissions; a broader assessment of other environmental externalities (e.g., air and water pollution, resource depletion) would provide a more comprehensive picture. Finally, longitudinal studies tracking firms over a longer period could help discern whether the current pollution haven outcome represents a transitional phase or a persistent trap, and under what conditions a shift toward a pollution halo dynamic might occur.

In summary, this research confirms that in China's current development paradigm, deeper GVCs engagement tends to come with a significant carbon cost, mediated by structural power imbalances and insufficient green technological diffusion. Moving beyond this paradigm requires a concerted effort to reshape the terms of GVCs participation, aligning economic integration with the imperative of ecological sustainability.

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Appendix A. Definition of Variables

Variable	Definition	Source
Dependent variables		
CE_Intensity	The focal firm's carbon emissions divided by its revenue.	Manually collect
Independent variables		
GVC1	The proportion of overseas business revenue to total revenue.	CSMAR
GVC2	The proportion of export revenue to total revenue.	CSMAR
Control variables		
Firm size	The natural log of the firm's total assets.	CSMAR
Leverage	The ratio of long-term debt to total assets.	CSMAR
ROA	Net income divided by the book value of total assets.	CSMAR
Tangibility	The ratio of tangible assets to total assets	CSMAR
Board size	The number of directors on board.	CSMAR
Diversity	The percentage of female directors.	CSMAR
Independent	The percentage of independent directors.	CSMAR
Firm age	The firm was listed on the SSE and SZSE for a period.	CSMAR
HHI	Herfindahl index: the sum of the square of the ratio of main business income to the total industry main business income.	CSMAR
SOE	An indicator variable coded 1 if the firm is state owned, and 0 otherwise.	CSMAR
Top1	Shareholding of the largest shareholder.	CSMAR
MB	Market-to-book ratio.	CSMAR
Other variables		
GVC3	The number of overseas subsidiaries.	CSMAR
GVC4	The number of overseas affiliated companies.	CSMAR
GVC5	The number of different countries and regions where the overseas subsidiaries are located.	CSMAR
Margin	Gross margin ratio, calculated as (Revenue - Cost of Goods Sold) / Revenue	CSMAR
Customer Stability	Top five clients compared to the previous year: Number of clients unchanged/5.	CNRDS
R&D Ratio	R&D expenditure as a percentage of operating revenue (%)	CSMAR
Green patent	The natural log of the number of green patent application.	CNRDS

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Table 1. Year distribution

Year	Frequency	Percentage
2009	1,129	3.56
2010	1,371	4.33
2011	1,564	4.94
2012	1,667	5.26
2013	1,659	5.24
2014	1,721	5.43
2015	1,847	5.83
2016	2,037	6.43
2017	2,402	7.58
2018	2,555	8.06
2019	2,700	8.52
2020	3,012	9.5
2021	3,380	10.67
2022	3,369	10.63
2023	1,276	4.03
Total	31,689	100

Note: This table illustrates the year distribution from 2009 to 2023.

Table 2. Summary statistics

	N	Mean	p50	SD	Min	Max
CE_Intensity	31,689	13.310	1.380	13.190	11.000	16.100
GVC1	31,689	0.130	0.200	0.010	0.000	0.660
GVC2	31,689	0.140	0.200	0.030	0.000	0.670
Firm size	31,689	22.230	1.230	22.030	20.450	24.850
ROA	31,689	0.040	0.040	0.040	-0.060	0.130
Leverage	31,689	0.040	0.060	0.010	0.000	0.220
Tangibility	31,689	0.220	0.150	0.200	0.020	0.540
Board size	31,689	8.510	1.370	9.000	6.000	11.000
Diversity	31,689	0.150	0.130	0.110	0.000	0.430
Independent	31,689	0.370	0.050	0.360	0.330	0.500
Firm age	31,689	9.800	7.480	8.000	0.000	24.000
HHI	31,689	0.170	0.110	0.140	0.050	0.440
SOE	31,689	0.360	0.480	0.000	0.000	1.000
Top1	31,689	34.900	13.960	33.210	13.580	62.200
MB	31,689	0.630	0.240	0.630	0.230	1.040

This table presents descriptive statistics on all variables in the sample. *CE_Intensity* is the focal firm's carbon emissions divided by its total revenue. *GVC1* is the proportion of overseas business revenue to total revenue. *GVC2* is the proportion of export revenue to total revenue. *Leverage* is the ratio of long-term debt to total assets. *ROA* is net income divided by the book value of total assets. *Tangibility* is the ratio of tangible assets to total assets. *Board size* is the number of directors on board. *Diversity* is the percentage of female directors. *Independent* is the percentage of independent directors. *Firm age* is the company was listed on the SSE and SZSE for a period. *HHI* is the Herfindahl Hirschman Index: the sum of the square of the ratio of main business income to the total industry main business income. *SOE* is an indicator variable coded 1 if the firm is state owned, and 0 otherwise. *Top1* is the proportion of shareholding of the largest shareholder. *MB* is the market-to-book ratio.

Table 3. Correlation matrix

Variables	(CE_Intensity)	(GVC1)	(GVC2)	(Firm size)	(ROA)	(Leverage)	(Tangibility)	(Board size)
CE_Intensity	1.000							
GVC1	0.0008	1.000						
GVC2	-0.038***	0.944***	1.000					
Firm size	0.838***	-0.050***	-0.087***	1.000				
ROA	0.042***	0.040***	0.047***	-0.062***	1.000			
Leverage	0.287***	-0.072***	-0.086***	0.455***	-0.224***	1.000		
Tangibility	0.146***	0.00	0.016***	0.105***	-0.111***	0.226***	1.000	
Board size	0.255***	-0.073***	-0.078***	0.257***	-0.014**	0.173***	0.141***	1.000
Diversity	-0.161***	0.053***	0.060***	-0.139***	0.054***	-0.091***	-0.058***	-0.118***
Independent	-0.029***	0.039***	0.030***	-0.00	-0.015***	-0.017***	-0.055***	-0.574***
Firm age	0.351***	-0.141***	-0.162***	0.447***	-0.227***	0.269***	0.093***	0.154***
HHI	0.106***	-0.035***	-0.043***	0.030***	-0.038***	-0.042***	0.029***	0.028***
SOE	0.348***	-0.185***	-0.189***	0.386***	-0.167***	0.295***	0.191***	0.283***
Top1	0.206***	-0.067***	-0.073***	0.185***	0.120***	0.078***	0.067***	0.011*
MB	0.428***	-0.064***	-0.081***	0.539***	-0.255***	0.344***	0.097***	0.150***
Variables	(Diversity)	(Independent)	(Firm age)	(HHI)	(SOE)	(Top1)	(MB)	
Diversity	1.000							
Independent	0.040***	1.000						
Firm age	-0.103***	-0.023***	1.000					
HHI	-0.058***	-0.000	-0.015***	1.000				
SOE	-0.210***	-0.060***	0.479***	0.031***	1.000			
Top1	-0.038***	0.049***	-0.048***	0.073***	0.208***	1.000		
MB	-0.075***	-0.021***	0.196***	0.043***	0.241***	0.158***	1.000	

***, **, * indicate the coefficients are significant at the 0.01, 0.05, and 0.10 levels, respectively, based on two-tailed statistical tests.

Table 4. Baseline regression

Variables	CE_Intensity	CE_Intensity	CE_Intensity	CE_Intensity
	(1)	(2)	(3)	(4)
GVC1	0.326*** (0.039)		0.116** (0.056)	
GVC2		0.258*** (0.039)		0.116** (0.054)
Firm size	0.966*** (0.010)	0.969*** (0.010)	0.836*** (0.013)	0.836*** (0.013)
ROA	2.520*** (0.160)	2.508*** (0.160)	2.030*** (0.111)	2.030*** (0.111)
Leverage	-2.457*** (0.152)	-2.464*** (0.152)	-0.714*** (0.097)	-0.715*** (0.097)
Tangibility	0.691*** (0.066)	0.688*** (0.066)	0.460*** (0.066)	0.459*** (0.066)
Board size	0.027*** (0.008)	0.027*** (0.008)	0.015*** (0.006)	0.015*** (0.006)
Diversity	-0.423*** (0.059)	-0.424*** (0.059)	-0.025 (0.041)	-0.025 (0.041)
Independent	-0.214 (0.189)	-0.200 (0.189)	0.210* (0.122)	0.209* (0.122)
Firm age	-0.001 (0.002)	-0.001 (0.002)	0.012 (0.009)	0.013 (0.009)
HHI	0.912*** (0.077)	0.912*** (0.077)	0.132** (0.057)	0.131** (0.057)
SOE	0.111*** (0.024)	0.105*** (0.024)	-0.004 (0.028)	-0.004 (0.028)
Top1	0.003*** (0.001)	0.003*** (0.001)	-0.000 (0.001)	-0.000 (0.001)
MB	-0.014 (0.036)	-0.018 (0.037)	-0.227*** (0.024)	-0.227*** (0.024)
Constant	-8.728*** (0.211)	-8.781*** (0.211)	-5.631*** (0.301)	-5.633*** (0.301)
Firm FE	No	No	Yes	Yes
Year FE	No	No	Yes	Yes
Observations	31,689	31,689	31,689	31,689
Adjusted R-square	0.7377	0.7369	0.9433	0.9433

Note: This table reports the effect of the embedding of GVCs on carbon emissions at the firm level. *GVC1* is measured by the ratio of overseas revenue to total revenue, and *GVC2* is measured by the export revenue ratio. Columns (1) and (2) report the results without firm and year fixed effects. Columns (3) and (4) report the results controlling for firm and year fixed effects. Variable definitions can be found in Appendix A. The standard errors in brackets are clustered at the firm level. ***, **, * indicate the coefficients are significant at the 0.01, 0.05, and 0.10 levels, respectively, based on two-tailed statistical tests.

Table 5. Robustness Checks

Variables	CE_Intensity						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
GVC1	0.120** (0.054)		0.005** (0.002)				
GVC2		0.122** (0.052)		0.005** (0.002)			
GVC3					0.012*** (0.003)		
GVC4						0.012*** (0.003)	
GVC5							0.020*** (0.005)
L.CE_Intensity			0.368*** (0.012)	0.369*** (0.012)			
Firm size	0.827*** (0.013)	0.827*** (0.013)	0.513*** (0.015)	0.513*** (0.015)	0.824*** (0.014)	0.825*** (0.013)	0.824*** (0.014)
ROA	2.034*** (0.105)	2.033*** (0.105)	1.983*** (0.095)	1.981*** (0.095)	2.054*** (0.110)	2.049*** (0.110)	2.051*** (0.110)
Leverage	-0.647*** (0.092)	-0.647*** (0.092)	-0.378*** (0.078)	-0.376*** (0.078)	-0.728*** (0.097)	-0.721*** (0.097)	-0.719*** (0.097)
Tangibility	0.434*** (0.058)	0.434*** (0.058)	0.266*** (0.054)	0.266*** (0.054)	0.463*** (0.066)	0.463*** (0.066)	0.461*** (0.066)
Board size	0.013** (0.005)	0.013** (0.005)	0.011** (0.005)	0.011** (0.005)	0.014** (0.006)	0.014** (0.006)	0.014** (0.006)
Diversity	-0.027	-0.028	-0.015	-0.016	-0.026	-0.028	-0.024

	(0.040)	(0.040)	(0.032)	(0.032)	(0.041)	(0.041)	(0.041)
Independent	0.199*	0.198*	0.165*	0.166*	0.196	0.198	0.192
	(0.115)	(0.115)	(0.098)	(0.098)	(0.122)	(0.122)	(0.122)
Firm age	0.015*	0.015*	0.003	0.003	0.012	0.012	0.011
	(0.009)	(0.009)	(0.007)	(0.007)	(0.009)	(0.009)	(0.009)
HHI	-8.706***	-8.695***	0.037	0.036	0.131**	0.129**	0.133**
	(2.160)	(2.161)	(0.046)	(0.046)	(0.057)	(0.057)	(0.057)
SOE	-0.007	-0.007	-0.022	-0.022	-0.003	-0.003	-0.005
	(0.027)	(0.027)	(0.020)	(0.020)	(0.028)	(0.028)	(0.028)
Top1	0.001	0.001	-0.000	-0.000	-0.000	-0.000	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
MB	-0.205***	-0.206***	-0.159***	-0.159***	-0.220***	-0.220***	-0.220***
	(0.024)	(0.024)	(0.020)	(0.020)	(0.024)	(0.024)	(0.024)
Constant	-3.991***	-3.995***	-3.200***	-3.206***	-5.357***	-5.386***	-5.364***
	(0.479)	(0.479)	(0.271)	(0.270)	(0.307)	(0.305)	(0.308)
Firm FE	Yes						
Year FE	No	No	Yes	Yes	Yes	Yes	Yes
Industry*Year FE	Yes	Yes	No	No	No	No	No
Observations	31,689	31,689	28,035	28,035	31,689	31,689	31,689
Adjusted R-square	0.9477	0.9477	0.9518	0.9518	0.9434	0.9434	0.9433

Note: Table 5 reports several robustness checks to validate the baseline findings. Columns (1) and (2) augment the baseline specification by including industry-by-year fixed effects to absorb sector-specific time-varying shocks, using *GVC1* and *GVC2*, respectively. Columns (3) and (4) add lagged carbon emission intensity as an additional control to account for persistence in firms' environmental performance. Columns (5) to (7) replace the main GVCs indicators with three alternative measures of global value chain participation: *GVC3* (number of overseas subsidiaries) and two additional GVCs indicators (*GVC4* and *GVC5*), constructed using alternative the number of overseas affiliated companies and the number of overseas subsidiaries, and the number of different countries and regions where the overseas subsidiaries are located. Variable definitions can be found in Appendix A. The standard errors in brackets are clustered at the firm level. ***, **, * indicate the coefficients are significant at the 0.01, 0.05, and 0.10 levels, respectively, based on two-tailed statistical tests.

Table 6. Instrumental Variables-2SLS

Variables	First Stage		2SLS	
	GVC1	GVC2	CE_Intensity	CE_Intensity
	(1)	(2)	(3)	(4)
GVC_ExposureIV	-0.002*** (0.000)	-0.001*** (0.000)		
GVC1			1.089*** (0.274)	
GVC2				1.139*** (0.290)
Firm size	0.017*** (0.003)	0.011*** (0.003)	0.955*** (0.011)	0.961*** (0.010)
ROA	-0.050 (0.052)	-0.016 (0.053)	2.580*** (0.166)	2.544*** (0.167)
Leverage	-0.100** (0.039)	-0.107*** (0.040)	-2.387*** (0.153)	-2.373*** (0.154)
Tangibility	0.085*** (0.019)	0.112*** (0.019)	0.645*** (0.069)	0.610*** (0.072)
Board size	-0.002 (0.002)	-0.003 (0.002)	0.031*** (0.008)	0.032*** (0.008)
Diversity	0.016 (0.021)	0.024 (0.021)	-0.442*** (0.062)	-0.452*** (0.063)
Independent	0.073 (0.063)	0.034 (0.063)	-0.242 (0.195)	-0.202 (0.196)
Firm age	-0.002*** (0.000)	-0.003*** (0.000)	0.001 (0.002)	0.002 (0.002)
HHI	-0.063*** (0.025)	-0.079*** (0.025)	0.944*** (0.081)	0.965*** (0.083)
SOE	-0.048*** (0.007)	-0.043*** (0.007)	0.153*** (0.029)	0.149*** (0.028)
Top1	-0.001*** (0.000)	-0.001*** (0.000)	0.003*** (0.001)	0.004*** (0.001)
MB	-0.044*** (0.012)	-0.041*** (0.011)	0.015 (0.039)	0.014 (0.040)
Constant	-0.045 (0.072)	0.111 (0.073)	-8.666*** (0.219)	-8.842*** (0.215)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	31,367	31,367	31,367	31,367
Adjusted R-square	-	-	0.7280	0.7229
Cragg-Donald Wald F	1012.369	895.457		
Kleibergen-Paap rk Wald F	125.468	111.009		

Note: Table 6 presents the instrumental variable (IV) estimates using a shift-share instrument to address potential endogeneity in firms' GVCs participation. The instrument, $GVC_ExposureIV$, is constructed as the interaction between firms' time-invariant exposure to global trade connectivity (proxied by their distance to the nearest port) and the annual growth in global trade volume. Columns (1) and (2) report the first-stage regressions for $GVC1$ and $GVC2$, while Columns (3) and (4) present the corresponding second-stage 2SLS estimates. All regressions include firm and year fixed effects, and standard errors are clustered at the firm level. The Cragg–Donald Wald F statistic and the Kleibergen-Paap rk Wald F statistic are reported to assess weak-instrument concerns. Variable definitions can be found in Appendix A. The standard errors in brackets are clustered at the firm level. ***, **, * indicate the coefficients are significant at the 0.01, 0.05, and 0.10 levels, respectively, based on two-tailed statistical tests.

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Table 7. New Export Tax Rebate Regulations

Variables	CE_Intensity	CE_Intensity
	(1)	(2)
DiD	0.224*** (0.014)	
DiD_placebo		0.015 (0.019)
Firm size	0.841*** (0.014)	0.828*** (0.013)
ROA	2.748*** (0.132)	2.024*** (0.105)
Leverage	-1.230*** (0.112)	-0.643*** (0.092)
Tangibility	0.364*** (0.070)	0.437*** (0.058)
Board size	0.010 (0.006)	0.013** (0.005)
Diversity	-0.062 (0.051)	-0.029 (0.040)
Independent	0.160 (0.146)	0.197* (0.115)
Firm age	-0.050*** (0.002)	0.015* (0.009)
HHI	0.609*** (0.066)	-8.709*** (2.156)
SOE	-0.081*** (0.029)	-0.007 (0.027)
Top1	-0.001 (0.001)	0.001 (0.001)
MB	-0.100*** (0.023)	-0.205*** (0.024)
Constant	-5.261*** (0.311)	-4.014*** (0.480)
Firm FE	Yes	Yes
Year FE	Yes	Yes
Observations	31,689	31,689
Adjusted R-square	0.8782	0.9476

Note: This table reports the difference-in-differences (DID) estimates examining the impact of the 2015 export tax rebate reform on firms' carbon emission intensity. The variable DiD is an interaction term equal to one for firms with pre-existing overseas business activities in the post-2015 period and zero otherwise. Column (1) presents the baseline DID estimate, while Column (2) reports a placebo test using 2013 as a fictitious policy implementation year. Variable definitions can be found in Appendix A. The standard errors in brackets are clustered at the firm level. ***, **, * indicate the coefficients are significant at the 0.01, 0.05, and 0.10 levels, respectively, based on two-tailed statistical tests.

Table 8. Expansion Capacity Channel

Variables	CE_Intensity	CE_Intensity	CE_Intensity	CE_Intensity
	(1)	(2)	(3)	(4)
GVC1*Margin	0.006** (0.003)			
GVC2*Margin		0.006** (0.002)		
GVC1*Customer_stability			0.113** (0.052)	
GVC2*Customer_stability				0.100** (0.050)
GVC1	-0.046 (0.082)		-0.051 (0.091)	
GVC2		-0.040 (0.078)		-0.048 (0.086)
Margin	-0.011*** (0.001)	-0.011*** (0.001)		
Customer_stability			-0.002 (0.012)	-0.002 (0.012)
Firm size	0.847*** (0.012)	0.847*** (0.012)	0.793*** (0.019)	0.794*** (0.019)
ROA	3.226*** (0.132)	3.223*** (0.132)	1.883*** (0.137)	1.883*** (0.137)
Leverage	-0.643*** (0.093)	-0.644*** (0.093)	-0.735*** (0.143)	-0.735*** (0.143)
Tangibility	0.404*** (0.061)	0.404*** (0.061)	0.398*** (0.093)	0.398*** (0.093)
Board size	0.013** (0.005)	0.013** (0.005)	0.014* (0.008)	0.014* (0.008)
Diversity	-0.027 (0.038)	-0.027 (0.038)	-0.003 (0.053)	-0.003 (0.053)
Independent	0.152 (0.115)	0.151 (0.115)	0.234 (0.169)	0.233 (0.169)
Firm age	0.009 (0.009)	0.009 (0.009)	0.019* (0.011)	0.019* (0.011)
HHI	0.110** (0.052)	0.110** (0.052)	0.198** (0.089)	0.197** (0.089)
SOE	-0.039 (0.027)	-0.039 (0.027)	-0.013 (0.036)	-0.012 (0.036)
Top1	-0.000 (0.001)	-0.000 (0.001)	0.000 (0.001)	0.000 (0.001)
MB	-0.227*** (0.023)	-0.227*** (0.023)	-0.222*** (0.033)	-0.221*** (0.033)
Constant	-5.501***	-5.505***	-4.798***	-4.800***

	(0.281)	(0.281)	(0.449)	(0.449)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	31,073	31,073	15,399	15,399
Adjusted R-square	0.9475	0.9475	0.9462	0.9462

Note: This table presents the mechanism test examining whether firms' expansion capacity moderate the effect of GVCs participation on carbon emission intensity. *Margin* denotes the gross profit margin, and the interaction terms $GVC1 \times Margin$ and $GVC2 \times Margin$ capture the heterogeneity in the emission effects of GVCs participation under different levels of pricing power or financial slack. In addition, we employ customer stability as an alternative proxy for firms' expansion capacity, which reflects the stability and persistence of customer relationships. The interaction terms $GVC1 \times Customer_Stability$ and $GVC2 \times Customer_Stability$ therefore capture how customer-relationship rigidity conditions the environmental consequences of GVCs participation. A positive and significant coefficient on any interaction term indicates that the corresponding dimension of expansion capacity amplifies the increase in carbon emission intensity associated with deeper engagement in GVCs. Variable definitions can be found in Appendix A. The standard errors in brackets are clustered at the firm level. ***, **, * indicate significance at the 0.01, 0.05, and 0.10 levels, respectively, based on two-tailed statistical tests.

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Table 9. Technological Innovation Channel

Variables	CE_Intensity	CE_Intensity	CE_Intensity	CE_Intensity
	(1)	(2)	(3)	(4)
GVC1*R&D ratio	0.024 (0.042)			
GVC2*R&D ratio		0.018 (0.039)		
GVC1*Green patent			0.034 (0.030)	
GVC2*Green patent				0.026 (0.032)
GVC1	-0.317 (0.770)		0.093 (0.093)	
GVC2		-0.188 (0.717)		0.123 (0.102)
R&D ratio	0.008 (0.006)	0.008 (0.006)		
Green patent			0.006 (0.007)	0.007 (0.008)
Firm size	0.799*** (0.034)	0.799*** (0.034)	0.809*** (0.023)	0.809*** (0.023)
ROA	2.243*** (0.226)	2.246*** (0.225)	1.956*** (0.200)	1.961*** (0.200)
Leverage	-0.280 (0.196)	-0.279 (0.195)	-0.526*** (0.198)	-0.524*** (0.198)
Tangibility	0.283** (0.130)	0.283** (0.130)	0.235* (0.137)	0.237* (0.137)
Board size	-0.016* (0.009)	-0.016* (0.009)	0.011 (0.010)	0.011 (0.010)
Diversity	-0.018 (0.085)	-0.019 (0.085)	0.024 (0.071)	0.024 (0.070)
Independent	-0.236 (0.211)	-0.234 (0.211)	0.124 (0.178)	0.123 (0.178)
Firm age	0.028* (0.017)	0.028* (0.017)	0.022 (0.019)	0.022 (0.019)
HHI	-0.067 (0.126)	-0.063 (0.126)	0.081 (0.100)	0.081 (0.100)
SOE	-0.035 (0.036)	-0.036 (0.036)	0.037 (0.039)	0.037 (0.039)
Top1	-0.001 (0.002)	-0.001 (0.002)	0.003* (0.001)	0.003* (0.001)
MB	-0.240*** (0.054)	-0.240*** (0.054)	-0.302*** (0.043)	-0.302*** (0.043)
Constant	-4.551***	-4.569***	-4.902***	-4.906***

	(0.832)	(0.833)	(0.527)	(0.526)
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	25,609	25,609	7,721	7,721
Adjusted R-square	0.9512	0.9512	0.9678	0.9678

Note: This table reports the estimation results for the technological innovation channel, which examines whether firms' technological upgrading mitigates the impact of GVCs participation on carbon emission intensity. *GVC1* is measured by the ratio of overseas revenue to total revenue, and *GVC2* is measured by the export revenue ratio. Technological innovation is proxied by two complementary indicators: the R&D ratio (R&D expenditure scaled by operating revenue) and the number of green patent applications (logarithm). Interaction terms between GVCs participation and these innovation measures are included to test the pollution halo hypothesis, which posits that technology acquisition and upgrading should weaken the emission-increasing effects of GVCs involvement. Variable definitions can be found in Appendix A. The standard errors in brackets are clustered at the firm level. ***, **, * indicate significance at the 0.01, 0.05, and 0.10 levels, respectively, based on two-tailed statistical tests.

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Table 10. Heterogeneity Tests

Panel A. Competitive Intensity				
Variables	High	Low	High	Low
	Competition	Competition	Competition	Competition
	CE_Intensity	CE_Intensity	CE_Intensity	CE_Intensity
	(1)	(2)	(3)	(4)
GVC1	0.086 (0.094)	0.158** (0.073)		
GVC2			0.077 (0.090)	0.165** (0.070)
Constant	-5.169*** (0.527)	-5.738*** (0.387)	-5.169*** (0.527)	-5.739*** (0.387)
Controls	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	11,294	20,092	11,294	20,092
Adjusted R-square	0.9527	0.9389	0.9527	0.9389
Panel B. Ownership Type				
Variables	SOE	Non-SOE	SOE	Non-SOE
	CE_Intensity	CE_Intensity	CE_Intensity	CE_Intensity
	(1)	(2)	(3)	(4)
GVC1	0.091 (0.084)	0.110* (0.064)		
GVC2			0.083 (0.085)	0.105* (0.061)
Constant	-3.986*** (0.534)	-5.476*** (0.385)	-3.984*** (0.534)	-5.478*** (0.385)
Controls	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	11,162	19,396	11,162	19,396
Adjusted R-square	0.9419	0.9399	0.9419	0.9399
Panel C. Pollution Attributes of the Industry				
Variables	High	Low	High	Low
	Pollution	Pollution	Pollution	Pollution
	CE_Intensity	CE_Intensity	CE_Intensity	CE_Intensity
	(1)	(2)	(3)	(4)
GVC1	-0.047 (0.098)	0.179*** (0.060)		
GVC2			-0.060 (0.092)	0.178*** (0.059)
Constant	-4.325*** (0.551)	-5.596*** (0.366)	-4.321*** (0.551)	-5.593*** (0.366)

Controls	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	8,634	22,519	8,634	22,519
Adjusted R-square	0.9529	0.9454	0.9529	0.9454
Panel D. Technological Sophistication				
Variables	High	Low	High	Low
	Technology	Technology	Technology	Technology
	CE_Intensity	CE_Intensity	CE_Intensity	CE_Intensity
	(1)	(2)	(3)	(4)
GVC1	0.157** (0.062)	0.025 (0.094)		
GVC2			0.157*** (0.060)	0.018 (0.088)
Constant	-5.570*** (0.354)	-4.551*** (0.584)	-5.574*** (0.355)	-4.550*** (0.584)
Controls	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	20,124	11,036	20,124	11,036
Adjusted R-square	0.9505	0.9405	0.9505	0.9405

Note: This table reports heterogeneity analyses examining how the impact of GVCs participation on carbon emission intensity varies across different firm and industry characteristics. Panel A splits the sample into high- and low-competition industries based on the Herfindahl-Hirschman Index (HHI). Panel B separates state-owned enterprises (SOEs) and non-SOEs. Panel C classifies firms into high- and low-pollution industries according to official industrial pollution categories. Panel D distinguishes high-technology and low-technology industries following national statistical definitions. Firm-level controls are included in all specifications. Variable definitions can be found in Appendix A. The standard errors in brackets are clustered at the firm level. ***, **, * indicate the coefficients are significant at the 0.01, 0.05, and 0.10 levels, respectively, based on two-tailed statistical tests.

Ethical Approval

This study uses publicly available firm-level financial and carbon emission data and does not involve human subjects, animal experiments, or sensitive personal information. Ethical approval was therefore not required.

Author Agreement

All authors have read and approved the final manuscript. All authors agree to be accountable for all aspects of the work and confirm that the manuscript has not been published previously and is not under consideration for publication elsewhere.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.