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Global Value Chain Participation, Financial Inclusion, and Environmental Degradation: Evidence from Developed and Emerging Countries Using MMQR

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Abstract

The environmental implications of globalization and financial inclusion have become a major concern for both policymakers and researchers. This study examines the heterogeneous relationships between Global Value Chain (GVC) participation, financial inclusion, and CO₂ emissions in a panel of 41 developed and emerging economies over the period 2004–2022. To capture differences across emission levels, the analysis employs the Method of Moments Quantile Regression (MMQR), complemented by Fixed Effects (FE), System GMM, and Common Correlated Effects Mean Group (CCEMG) estimators for robustness. The findings reveal substantial heterogeneity across the conditional distribution of CO₂ emissions. Forward and backward GVC participation exhibit distinct environmental associations across emission levels, while financial inclusion plays a differentiated moderating role in these relationships. The conditional marginal effects further show that the environmental implications of GVC participation depend on the level of financial inclusion. The robustness analysis confirms the consistency of these findings across alternative estimators. Overall, the results suggest that the environmental consequences of globalization depend on both countries' emission levels and the role of financial inclusion in shaping the effects of GVC participation. From a policy perspective, the findings highlight the need to align financial development with environmental objectives. Strengthening green finance frameworks and environmental regulations can help ensure that deeper integration into global production networks supports sustainable development rather than increasing environmental degradation.

Keywords: CCEMG; CO₂ emissions; financial inclusion; global value chains; MMQR; System GMM



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1. Introduction

Environmental degradation has become a major global challenge, threatening economic sustainability, public health, and human welfare. According to the Intergovernmental Panel on Climate Change (Portner et al., 2022), global temperatures may exceed the critical 1.5 °C threshold unless substantial mitigation efforts are implemented. Beyond ecological damage, climate change generates significant economic costs by reducing productivity and increasing social vulnerability through pollution-related externalities (Landrigan et al., 2018). Recent evidence also shows that pollution remains a major cause of premature mortality worldwide, creating substantial pressures on public health

systems and economic performance, particularly in rapidly industrializing economies (Lelieveld et al., 2015). Therefore, reconciling economic development with environmental sustainability has become a central objective of international initiatives, including the Paris Agreement and the Sustainable Development Goals (SDGs). Within the framework of the 2030 Agenda, sustainable development requires balancing economic growth, social inclusion, technological progress, and environmental protection (United Nations, 2015). In this context, innovation and sustainable production systems contribute to SDG 8 and SDG 9, while reducing carbon emissions and promoting responsible production are essential to achieving SDG 12 and SDG 13 (Danil et al., 2025; Caglar et al., 2026).

Against this background, the expansion of Global Value Chains (GVCs) has fundamentally transformed international production systems. Instead of concentrating production within national borders, firms increasingly divide production activities across countries to benefit from specialization, cost advantages, and efficiency gains through international production networks (Baldwin, 2016; Grossman & Rossi-Hansberg, 2008). This fragmentation has created complex cross-border linkages that affect both economic performance and environmental outcomes. Recent studies show that GVC participation can enhance productivity, facilitate technological diffusion, and support industrial upgrading, especially in emerging economies through access to international markets and global knowledge networks (World Bank, 2020; Antràs, 2021). However, the environmental consequences of GVC integration remain ambiguous. While global production networks may promote cleaner technologies, efficiency improvements, and knowledge transfer, they may also increase resource use and reinforce carbon-intensive production activities. Consequently, understanding whether GVC participation supports sustainable production or increases environmental pressures remains an important research question (Shi & Yang, 2025).

At the same time, financial inclusion has emerged as an important dimension of sustainable development strategies. By improving access to financial services, FI can facilitate investment, encourage technological adoption, and enhance economic participation (J. Li et al., 2022). However, its environmental effects are not necessarily uniform. Greater financial access may support cleaner technologies, sustainable investments, and environmentally efficient production. Conversely, it may stimulate consumption, industrial expansion, and investment in carbon-intensive sectors, thereby increasing environmental pressures (Ha & Nguyen, 2025; Sajid et al., 2023; Oanh, 2024; Ben Cheikh & Rault, 2024). Thus, the environmental consequences of financial inclusion depend largely on how financial resources are allocated and the types of activities they support.

The interaction between financial inclusion and global production networks has become increasingly relevant because firms engaged in GVC activities depend on financial resources for trade, investment, risk management, and technological upgrading (Xu et al., 2024). In this context, financial inclusion may influence whether GVC participation generates sustainable or carbon-intensive outcomes. Access to finance can help firms adopt advanced technologies, improve production efficiency, and invest in cleaner processes (Arshad & Parveen, 2024; Mwita et al., 2025; Rizwan Ullah et al., 2025). However, it may also facilitate investment in resource-intensive sectors and reinforce carbon-dependent production patterns (H. Wang et al., 2015; Ben Cheikh & Rault, 2024). Despite this potential interaction, the joint role of GVC participation and financial inclusion in shaping environmental outcomes remains underexplored.

Moreover, the environmental effects of globalization and financial inclusion are likely to differ across countries because of differences in economic development, industrial structures, institutional conditions, technological capabilities, and positions within global production networks. This issue is particularly important for countries occupying different positions in GVCs, ranging from knowledge-intensive activities to downstream assembly

operations (Koopman et al., 2014; S. Wang et al., 2022). Consequently, the environmental impact of GVC integration may vary depending on production structures, energy systems, and financial conditions. Mean-based approaches may therefore overlook important differences across countries and emission levels. To address this issue, this study uses a balanced panel of 41 developed and emerging economies over the period 2004–2022, covering a period characterized by major transformations in global production networks and financial systems.

Despite the growing literature on globalization and environmental sustainability, several gaps remain. First, existing studies largely rely on mean-based estimators, which may obscure differences across the distribution of CO₂ emissions. Such approaches may provide an incomplete picture of the relationship between GVC participation, financial inclusion, and environmental degradation. Second, the moderating role of financial inclusion in the GVC–environment relationship remains insufficiently explored. Third, increasing global interdependence requires econometric approaches capable of accounting for cross-sectional dependence and common shocks (Pesaran, 2015).

To address these gaps, this study examines the effects of GVC participation and financial inclusion on CO₂ emissions by distinguishing between forward participation (DVX), backward participation (FVA), and aggregate GVC integration. The empirical analysis applies the Method of Moments Quantile Regression (MMQR) developed by Machado and Silva (2019), which allows the identification of heterogeneous effects across the conditional distribution of emissions. The results are further assessed using Fixed Effects (FE), System GMM, and Common Correlated Effects Mean Group (CCEMG) estimators to address potential issues related to unobserved heterogeneity, endogeneity, and cross-sectional dependence.

This study makes four contributions. First, it provides a comprehensive analysis of the environmental effects of different dimensions of GVC participation by distinguishing between forward, backward, and aggregate integration. Second, it extends the globalization–environment literature by incorporating financial inclusion as a moderating factor. Third, it provides new evidence on heterogeneous relationships between globalization, financial development, and environmental degradation across different emission levels. Finally, it offers policy insights for aligning global integration and financial development with environmental sustainability objectives.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the data, variables, and empirical methodology. Section 4 discusses the empirical results. Section 5 concludes and provides policy recommendations.

2. Literature Review

The environmental implications of globalization and financial development have attracted growing attention in the recent literature. The expansion of Global Value Chains (GVCs) and the increasing importance of financial inclusion have generated an important debate regarding their consequences for environmental sustainability. Existing studies provide mixed evidence, reflecting the coexistence of different transmission mechanisms. This suggests that the relationship between globalization, financial development, and environmental degradation depends strongly on countries' economic structures, technological capabilities, and development levels. This section reviews the theoretical and empirical literature on the environmental effects of GVC participation, the role of financial inclusion, and the potential interaction between these two dimensions.

The expansion of GVCs has fundamentally transformed international production systems by enabling countries to specialize in different stages of production (De Oliveira et al., 2026). The environmental effects of GVC participation are commonly analyzed

through the framework of scale, composition, and technique effects introduced by Grossman and Krueger (1995). The scale effect suggests that greater production activity and energy demand may increase emissions (Chou & Wang, 2020). In contrast, the technique and composition effects highlight the potential environmental benefits associated with technological diffusion, structural upgrading, and improvements in production efficiency. Therefore, the net environmental impact of GVC integration remains theoretically uncertain and depends on countries' positions within global production networks.

The Pollution Haven Hypothesis (PHH) provides another perspective on the globalization–environment relationship by suggesting that pollution-intensive activities may relocate to countries with weaker environmental regulations (Taylor, 2004). Within the context of GVCs, this mechanism is particularly relevant for backward participation, as developing economies often specialize in assembly and processing activities that may involve higher energy intensity. Consequently, the environmental outcomes of GVC integration depend not only on the degree of participation but also on the type of activities performed within global production networks.

Empirical evidence on the GVC–environment nexus remains inconclusive. Some studies find that deeper integration into global production networks increases carbon emissions by expanding industrial activity and energy consumption. Chen and Zhao (2022) show that production fragmentation can intensify environmental pressures, while S. Wang et al. (2022) argue that efficiency gains from GVC integration may be insufficient to offset the environmental costs associated with production expansion, particularly in developing economies. Conversely, other studies emphasize the environmental benefits of GVC participation through technological upgrading and knowledge transfer. Zhu et al. (2025), for example, show that forward participation can reduce emission intensity by improving access to cleaner technologies and higher production standards. These contrasting findings indicate that the environmental effects of GVC participation are not uniform but depend on countries' development levels, production structures, and positions within global value chains.

Alongside globalization, financial inclusion has emerged as an important component of sustainable development strategies (Voica, 2017; Demircuc-Kunt et al., 2018). However, its environmental effects remain context-dependent. On the one hand, financial inclusion can improve environmental performance by relaxing financing constraints, supporting green innovation, and facilitating investment in cleaner technologies. These mechanisms are consistent with the technique effect and the possibility of achieving greater environmental efficiency through financial development. On the other hand, broader financial access may stimulate consumption, industrial expansion, and investment in carbon-intensive sectors, thereby increasing environmental pressures. Thus, the environmental role of financial inclusion depends largely on the allocation of financial resources and the productive activities they support.

Empirical evidence also reveals mixed results. Uddin (2020), using a panel of 115 countries, finds that financial development increases environmental degradation during the early stages of industrialization. Similarly, Farah et al. (2026) show that financial inclusion may simultaneously encourage green investment while increasing emissions through stronger economic activity and energy demand. These findings suggest that the finance–environment relationship varies across institutional conditions and stages of development.

Despite the growing literature on GVC participation and financial inclusion, limited attention has been devoted to their joint environmental effects. From a theoretical perspective, firms involved in global production networks require financial resources to finance trade, manage risks, and support technological upgrading (BIS, 2017). Therefore, finan-

cial inclusion may influence how GVC participation affects environmental outcomes by determining the accessibility and allocation of financial resources.

This interaction involves two contrasting mechanisms. First, financial inclusion may strengthen the environmental benefits of GVC participation by facilitating technological adoption, improving production efficiency, and supporting cleaner production processes. Second, it may amplify environmental pressures by accelerating industrial expansion and increasing energy demand. Consequently, the environmental impact of GVC integration may depend not only on the extent of participation in global production networks but also on the capacity of financial systems to support sustainable activities.

However, important gaps remain in the existing literature. Most empirical studies rely on mean-based estimators, such as OLS or conventional GMM approaches, which assume homogeneous effects across countries (Koenker & Bassett, 1978). Such methods may overlook differences across the distribution of CO₂ emissions and fail to capture heterogeneous relationships between globalization, financial inclusion, and environmental degradation. Therefore, limited evidence exists on how the interaction between GVC participation and financial inclusion varies between low- and high-emission economies. Addressing this gap motivates the empirical approach adopted in this study.

3. Data and Methodology

3.1. Data

This study examines the environmental consequences of global value chain (GVC) participation and financial inclusion (FI) using a balanced panel dataset of 41 developed and emerging economies over the period 2004–2022. The dependent variable is CO₂ emissions per capita, which is widely used in the environmental economics literature as an indicator of environmental pressure generated by economic activities, industrial development, and energy consumption (Solarin & Al-Mulali, 2018; Sobirov et al., 2025).

To measure countries' integration into global production networks, this study relies on three GVC participation indicators developed within the framework of Koopman et al. (2014). The first indicator is forward GVC participation (DVX), which captures the domestic value added incorporated into other countries' exports. This measure reflects a country's upstream position in global production networks. The second indicator is backward GVC participation (FVA), which measures the foreign value added embodied in domestic exports and represents downstream integration. The third indicator is the overall GVC participation index, calculated as the sum of forward and backward participation. Since these indicators capture different dimensions of global integration and may generate multicollinearity problems when included simultaneously, they are introduced separately in alternative model specifications (Coveri & Zanfei, 2023; J. Liu & Kinkyo, 2026).

The empirical analysis also incorporates several control variables identified as important determinants of environmental outcomes. Trade openness, measured as the ratio of exports plus imports to GDP, captures the degree of international economic integration and exposure to global markets (Yang et al., 2022). Real GDP per capita is included to control for the scale effect of economic development and production activities (Habimana Simbi et al., 2025). Urbanization, measured as the share of the population living in urban areas, captures demographic changes and structural transformation processes that may influence energy demand and environmental pressures (Raihan & Tuspekova, 2022).

Financial inclusion is introduced as a key explanatory variable and is measured using a composite index constructed through Principal Component Analysis (PCA). The index combines two indicators of formal financial infrastructure: the number of automated teller machines (ATMs) per 100,000 adults and the number of commercial bank branches per 100,000 adults. Although financial inclusion is a multidimensional concept that may also

include digital financial services, mobile banking, credit access, and fintech development, the limited availability of these indicators across countries and over time prevents their consistent use in a balanced panel covering 2004–2022. Therefore, this study focuses on physical access to formal financial services, which remains a widely accepted dimension of financial inclusion in cross-country empirical research (Demirguc-Kunt et al., 2018; Zoubida et al., 2025).

The PCA approach provides an appropriate method for combining these indicators into a single index by extracting their common underlying dimension while reducing information redundancy. The results of the PCA, presented in Appendix A.2, show that the first principal component has an eigenvalue of 1.826 and explains 91.30% of the total variance. Based on the Kaiser criterion, only the first component is retained. Both indicators display identical positive factor loadings (0.7071), indicating an equal contribution to the construction of the financial inclusion index. The final index is normalized between 0 and 1, with higher values indicating greater access to formal financial services.

The baseline empirical model is specified as follows:

$$CO_{2\{it\}} = \alpha + \beta_1 GVC_{\{it\}} + \beta_2 FI_{\{it\}} + \beta_3 GDP_{\{it\}} + \beta_4 Trade_{\{it\}} + \beta_5 Urban_{\{it\}} + \varepsilon_{\{it\}}$$

To investigate the moderating role of financial inclusion, the model is extended by incorporating an interaction term between GVC participation and financial inclusion:

$$CO_{2\{it\}} = \alpha + \beta_1 GVC_{\{it\}} + \beta_2 FI_{\{it\}} + \beta_3 (GVC_{\{it\}} \times FI_{\{it\}}) + \beta_4 GDP_{\{it\}} + \beta_5 Trade_{\{it\}} + \beta_6 Urban_{\{it\}} + \varepsilon_{\{it\}}$$

The coefficient of the interaction term allows us to determine whether financial inclusion amplifies or mitigates the environmental consequences of global value chain participation.

To account for possible heterogeneity in the structure of global integration, three alternative specifications are estimated. Each model includes, respectively, the aggregate GVC participation index, forward participation (DVX), and backward participation (FVA). This strategy allows a more detailed assessment of how different forms of GVC integration influence environmental outcomes.

The final dataset contains 41 countries observed annually between 2004 and 2022, resulting in 779 observations. The complete list of countries is provided in Appendix A.1. Macroeconomic and environmental variables are obtained from the World Development Indicators (WDI), while GVC participation indicators are obtained from the OECD Trade in Value Added (TiVA) database, 2025 edition.

Table 1 presents the descriptive statistics of the variables used in the empirical analysis. The results highlight important differences among the countries included in the sample, reflecting the diversity of developed and emerging economies. CO₂ emissions show substantial variation, with values ranging from 0.31 to 33.07 metric tons per capita, indicating significant differences in environmental performance across countries. The GVC indicators also display considerable heterogeneity. Forward participation ranges from 7.78 to 44.86, while backward participation varies between 1.87 and 54.81, reflecting differences in countries' positions within global production networks. Similarly, financial inclusion shows noticeable cross-country disparities, confirming unequal access to formal financial infrastructure. GDP per capita exhibits the largest dispersion among the variables, highlighting significant development gaps within the sample. Trade openness and urbanization also show considerable variation, reflecting differences in international integration patterns and demographic structures.

The Jarque–Bera test indicates that most variables deviate from normality. However, the null hypothesis of a normal distribution cannot be rejected for the aggregate GVC index at the 5% significance level. This evidence supports the use of econometric techniques capable of capturing heterogeneous effects across the conditional distribution of CO₂

emissions, particularly the Method of Moments Quantile Regression (MMQR), which does not require strict normality assumptions and allows for the analysis of distributional heterogeneity (Miyan et al., 2026; Shan et al., 2024).

Table 1. Results of descriptive statistics.

Variable	Obs	Mean	Min.	Max.	Std. Dev.	Skewness	Kurtosis	Jarque–Bera (J-B)	p-Value
CO ₂	779	6.6644	0.3100	33.0700	5.1466	1.2754	5.6934	144.89	0.0000
DVX	779	20.2169	7.7810	44.8600	7.1000	0.7885	3.4093	55.73	0.0000
FVA	779	24.1582	1.8740	54.8100	10.5708	0.2159	2.4389	21.93	0.0000
GVC	779	44.3751	21.9090	66.0480	8.4776	−0.2062	3.0037	5.52	0.0632
FI	779	0.5123	0.0000	1.0000	0.2245	−0.1667	2.4672	6.04	0.0487
GDP	779	20,723.5100	775.8471	97,793.5400	20,199.0400	1.2121	3.9985	110.15	0.0000
Trade	779	86.8240	22.11	258.78	47.0767	1.0418	3.706876	85.22	0.0000
Urban	779	70.5034	18.9814	95.6003	16.7247	−0.8450	3.2368	59.58	0.0000

Figure 1 illustrates the evolution of the main variables over the period 2004–2022, highlighting changes in environmental degradation, GVC participation, financial inclusion, economic development, trade openness, and urbanization across the selected economies.

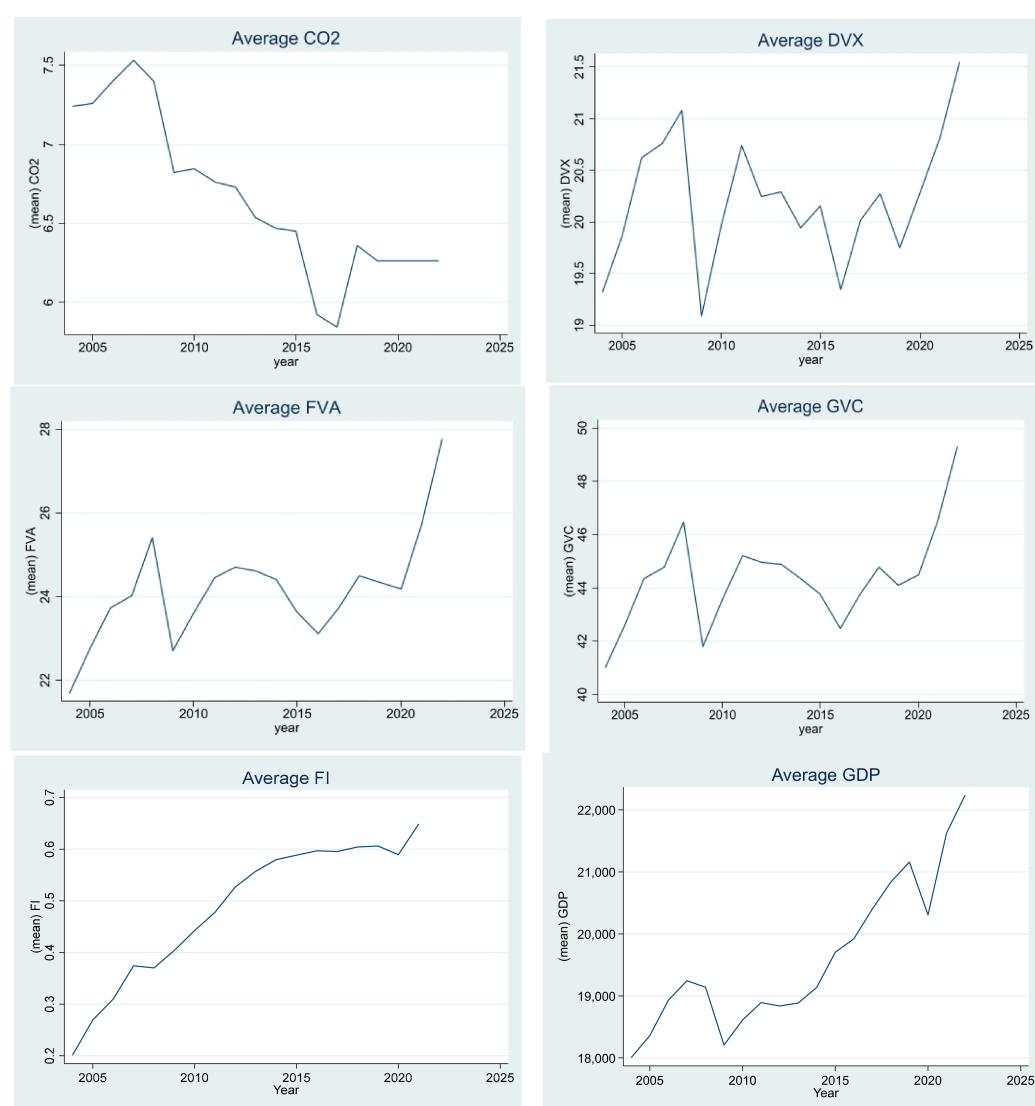


Figure 1. Cont.

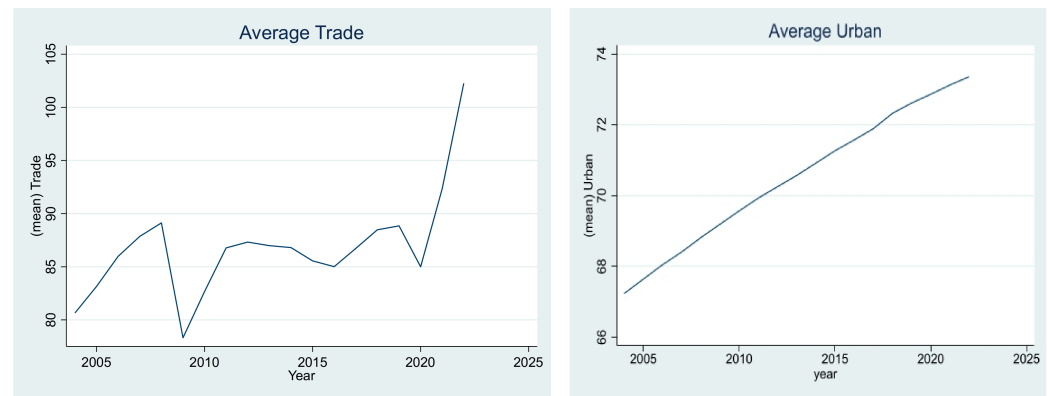


Figure 1. Evolution of environmental degradation (CO₂ emissions), global value chain participation (GVC), financial inclusion, trade openness, economic growth (GDP per capita), and urbanization in a panel of 41 developed and emerging economies during the period 2004–2022. Source: Authors’ computations.

3.2. Econometric Methodology

The relationship between global value chain participation, financial inclusion, and environmental degradation is unlikely to be homogeneous across countries. In particular, the environmental effects of global integration and financial development may differ depending on countries’ initial emission levels, technological capacities, and production structures. Therefore, estimators based solely on conditional mean effects may conceal important differences across the distribution of CO₂ emissions.

To address this limitation, this study adopts the Method of Moments Quantile Regression (MMQR) with fixed effects developed by Machado and Silva (2019). Unlike conventional mean-based panel estimators, MMQR allows the effects of explanatory variables to vary across different points of the conditional distribution of CO₂ emissions. This feature is particularly relevant in environmental studies, where the determinants of emissions may operate differently across low-emission and high-emission economies.

The MMQR approach offers several advantages in the context of this study. First, it combines the flexibility of quantile regression with panel data techniques by controlling for unobserved country-specific characteristics. Second, it does not require the assumption of normally distributed errors and is therefore suitable given the non-normal distribution of several variables reported in the descriptive statistics. Third, it allows the identification of heterogeneous effects across emission levels, providing a more detailed understanding of how GVC participation and financial inclusion are associated with environmental outcomes.

The baseline MMQR model is specified as follows:

$$Q_{\{CO2_{it}\}}(\tau|X_{it}) = \alpha_i + \beta_{1(\tau)}GVC_{it} + \beta_{2(\tau)}FI_{it} + \beta_{3(\tau)}GDP_{it} + \beta_{4(\tau)}Trade_{it} + \beta_{5(\tau)}Urban_{it} + \varepsilon_{it}(\tau)$$

where $Q(\tau)$ represents the conditional quantile function at quantile $\tau \in (0, 1)$, and $\beta(\tau)$ captures the heterogeneous effects of explanatory variables across different emission levels.

To examine whether financial inclusion modifies the environmental association of GVC participation, an interaction term between GVC participation and financial inclusion is introduced:

$$Q_{\{CO2_{it}\}}(\tau|X_{it}) = \alpha_i + \beta_{1(\tau)}GVC_{it} + \beta_{2(\tau)}FI_{it} + \beta_{3(\tau)}(GVC_{it} \times FI_{it}) + \beta_{4(\tau)}GDP_{it} + \beta_{5(\tau)}Trade_{it} + \beta_{6(\tau)}Urban_{it} + \varepsilon_{it}(\tau)$$

The interaction coefficient does not directly represent the moderating effect of financial inclusion. Following Brambor et al. (2006), the moderating role is evaluated through the conditional marginal effect of GVC participation:

$$\frac{dCO_{2i,t}}{dGVC_{i,t}} = \beta_1 + \beta_3 FI_{i,t}$$

This approach makes it possible to assess whether financial inclusion mitigates or intensifies the environmental association of GVC participation depending on the level of financial inclusion and the position of countries within the CO₂ emission distribution.

Although MMQR provides valuable evidence on heterogeneous relationships, it does not completely eliminate potential endogeneity problems related to reverse causality and omitted variables. For example, countries experiencing higher environmental pressures may adopt stricter regulations that influence their participation in global production networks. Similarly, environmental concerns may affect financial sector development policies. Therefore, MMQR estimates are interpreted as conditional relationships rather than strict causal effects.

To assess the robustness of the findings and address potential econometric concerns, several complementary estimators are employed.

First, the Fixed Effects (FE) estimator is used as a benchmark model. This approach controls for unobserved time-invariant country characteristics, such as institutional quality, geographical conditions, and structural economic differences, which may simultaneously affect GVC participation and environmental outcomes.

Second, the System Generalized Method of Moments (System-GMM) estimator developed by Arellano and Bover (1995) and Blundell and Bond (1998) is employed to address potential endogeneity concerns. This estimator is particularly appropriate for dynamic panel settings in which feedback effects between variables may exist. By using lagged values of endogenous variables as internal instruments, System-GMM helps mitigate potential biases arising from reverse causality and omitted variables. The validity of the instruments is assessed using the Hansen test, while the absence of second-order serial correlation is examined using the Arellano–Bond AR(2) test.

Third, given the increasing interdependence among economies, the analysis accounts for common global shocks, international production linkages, and financial spillovers that may generate cross-sectional dependence and heterogeneous responses across countries. Accordingly, the Common Correlated Effects Mean Group (CCEMG) estimator proposed by Pesaran (2006) is employed. This method accounts for unobserved common factors by incorporating cross-sectional averages of the dependent and explanatory variables while allowing slope coefficients to vary across countries.

The preliminary diagnostic tests confirm the relevance of these methodological choices by indicating the presence of cross-sectional dependence and heterogeneous country responses. Consequently, the combination of MMQR, FE, System-GMM, and CCEMG estimators provides a comprehensive empirical strategy. MMQR identifies heterogeneous effects across emission levels, FE provides a baseline within-country estimation, System-GMM addresses potential endogeneity concerns, and CCEMG controls for common shocks and parameter heterogeneity.

Together, these complementary approaches provide a more reliable assessment of the relationship between GVC participation, financial inclusion, and environmental degradation across developed and emerging economies.

4. Results and Discussion

4.1. Preliminary Econometric Diagnostics

Before presenting the main estimation results, several preliminary diagnostic tests are conducted to assess the main econometric characteristics of the panel dataset and identify the most appropriate estimation strategy. Given the strong international integration of the countries included in the sample, cross-sectional dependence is an important concern. Countries are connected through global trade, financial flows, production networks, and common international shocks, implying that developments in one economy may affect others (Pesaran, 2015).

Therefore, the Pesaran cross-sectional dependence (CD) test is first applied to all variables. The results reported in Table 2 show statistically significant cross-sectional dependence for CO₂ emissions, all GVC indicators (DVX, FVA, and GVC), financial inclusion, and the control variables. These findings suggest that conventional first-generation panel techniques, which assume cross-sectional independence, may not be appropriate for this dataset.

Table 2. Outcomes of CD, CIPS, and CADF tests.

Variables	CD	CIPS		CADF	
		I(0)	I(1)	I(0)	I(1)
CO ₂	2.40 ***	−1.652	−3.670 ***	−1.921	−2.274 ***
DVX	19.61 ***	−1.384	−3.499 ***	−1.408	−2.386 ***
FVA	24.90 ***	−1.432	−3.591 ***	−1.461	−2.594 ***
GVC	42.31 ***	−1.432	−4.053 ***	−1.430	−2.701 ***
FI	18.46 ***	−1.324	−3.126 ***	−1.485	−2.621 ***
GDP	48.86 ***	−1.267	−2.448 ***	−1.556	−1.915 ***
Trade	65.42 ***	−1.562	−2.753 ***	−1.134	−2.572 ***
Urban	94.48 ***	−1.375	−1.452 ***	−1.564	−2.687 ***

Note: Authors' computations. *** denotes the 1% significance level..

Consequently, second-generation panel unit root tests, namely the Cross-sectionally Augmented Dickey–Fuller (CADF) and Cross-sectionally Augmented IPS (CIPS) tests, are employed. These approaches account for common factors affecting countries simultaneously and provide more reliable evidence in the presence of cross-sectional dependence.

The results show that the variables are generally non-stationary in levels but become stationary after first differencing. Therefore, all variables can be considered integrated of order one, I(1). This finding highlights the need to examine whether a long-run equilibrium relationship exists among the variables before estimating the models in levels.

Accordingly, the presence of a long-run relationship is examined using the Westerlund (2007) panel cointegration test. This approach is particularly suitable because it allows for cross-sectional dependence and heterogeneous adjustment processes across countries. Unlike traditional cointegration tests, the Westerlund framework is based on error-correction dynamics and evaluates whether deviations from long-run equilibrium are corrected over time. The test reports four statistics: two group statistics (Gt and Ga), which examine cointegration at the country level, and two panel statistics (Pt and Pa), which evaluate the existence of a common long-run relationship across the entire panel.

As reported in Table 3, the null hypothesis of no cointegration is rejected across the three model specifications. Both group and panel statistics are statistically significant, suggesting the existence of a long-run equilibrium association among CO₂ emissions, GVC participation, financial inclusion, and the control variables. These findings support the estimation of the models in levels and indicate that the estimated coefficients should be interpreted as long-run conditional relationships rather than short-run correlations. However,

the existence of cointegration does not imply causality. In particular, although the empirical framework addresses several econometric issues, the estimated coefficients should not be interpreted as definitive causal effects because potential sources of endogeneity may remain.

Table 3. Westerlund (2007) Panel Cointegration Test Results.

Model	Statistic	Test Statistic	p-Value
Model 1 (DVX)	Gt	−3.892 ***	0.011
	Ga	−12.845 **	0.026
	Pt	−11.342 ***	0.006
	Pa	−13.891 ***	0.017
Model 2 (FVA)	Gt	−3.745 ***	0.014
	Ga	−12.345 **	0.031
	Pt	−10.987 ***	0.008
	Pa	−13.456 **	0.022
Model 3 (GVC)	Gt	−3.612 ***	0.019
	Ga	−11.987 **	0.042
	Pt	−10.654 **	0.012
	Pa	−12.987 **	0.028

Note: Authors' computations. ***, ** denote significance at the 1% and 5% levels, respectively.

Potential multicollinearity among the explanatory variables is examined using the Variance Inflation Factor (VIF) test. Table 4 shows that all VIF values remain below the commonly accepted threshold of 5. The mean VIF ranges between 1.47 and 2.28 across the three specifications, indicating that multicollinearity is unlikely to affect the reliability of the estimated coefficients.

Table 4. Multicollinearity Test (Variance Inflation Factor).

Variables	Model 1 (DVX)	Model 2 (FVA)	Model 3 (GVC)
DVX	1.10		
FVA		2.81	
GVC			2.40
FI	1.50	1.55	1.58
GDP	1.88	2.15	1.90
Trade	1.34	3.40	2.72
Urban	1.52	1.51	1.52
Mean VIF	1.47	2.28	2.02

Note: Authors' computations. All VIF values are well below the conventional threshold of 5, indicating that multicollinearity is not a concern.

Another important feature of the dataset is the possibility that the effects of GVC participation, financial inclusion, and control variables vary across countries. To investigate this issue, the Pesaran and Yamagata (2008) slope heterogeneity test is conducted. The results presented in Table 5 indicate that both the Δ and adjusted Δ statistics are positive and statistically significant across all model specifications. Therefore, the hypothesis of homogeneous slope coefficients is rejected.

Table 5. Outcomes of slope heterogeneity test.

Model	Δ	p-Value	Δ_{adj}	p-Value
Model 1 (DVX)	15.459 ***	0.000	18.713 ***	0.000
Model 2 (FVA)	15.252 ***	0.000	18.341 ***	0.000
Model 3 (GVC)	15.387 ***	0.000	18.521 ***	0.000

Note: Authors' computations. *** denotes significance at the 1% significance level.

This evidence confirms the existence of heterogeneous relationships across countries, which may result from differences in economic structures, technological capabilities, institutional environments, and development levels. Accordingly, the presence of slope heterogeneity supports the use of estimation techniques that allow coefficients to vary across countries and across the conditional distribution of CO₂ emissions, particularly MMQR and CCEMG.

4.2. Baseline MMQR Estimates

The MMQR estimates reported in Tables 6–8 indicate that the relationship between GVC participation, financial inclusion, and CO₂ emissions is heterogeneous across the conditional distribution of emissions. By allowing coefficients to vary across quantiles, the MMQR approach provides evidence on how these relationships differ between low- and high-emission economies. The location parameter reflects the estimated conditional effect of the explanatory variables, whereas the scale parameter captures their influence on the dispersion of the conditional distribution.

Table 6. Baseline MMQR Results: DVX Model.

Variables	Location	Scale	q10	q25	q50	q75	q90
DVX	−0.1929524 *** (0.001)	−0.0320473 0.463	−0.1458794 ** (0.028)	−0.1634075 *** (0.003)	−0.184447 *** (0.001)	−0.2107724 *** (0.004)	−0.2597458 ** (0.043)
FI	−11.55492 *** (0.000)	−4.191285 ** 0.027	−5.398521 * (0.073)	−7.690917 *** (0.001)	−10.44255 *** (0.000)	−13.8855 *** (0.000)	−20.29044 *** (0.000)
DVX × FI	0.6347803 *** (0.000)	0.0976498 0.177	0.4913467 *** (0.000)	0.5447556 *** (0.000)	0.6088639 *** (0.000)	0.6890788 *** (0.000)	0.8383029 *** (0.000)
GDP	0.000226 *** (0.000)	−0.0000164 0.547	0.0002501 *** (0.000)	0.0002411 *** (0.000)	0.0002304 *** (0.000)	0.0002169 *** (0.000)	0.0001918 ** (0.016)
Trade	0.0262698 *** (0.000)	0.0184309 *** 0.000	−0.0008026 (0.929)	0.0092781 (0.163)	0.0213782 *** (0.001)	0.0365184 *** (0.000)	0.0646837 *** (0.000)
Urban	0.0142453 (0.388)	0.0307023 ** 0.012	−0.0308519 (0.116)	−0.0140595 (0.362)	0.0060968 (0.687)	0.0313174 (0.133)	0.0782352 ** (0.034)

Note: Authors' computations. ***, **, and * 1%, 5%, and 10% levels of significance, respectively.

Table 7. Baseline MMQR Results: FVA Model.

Variables	Location	Scale	q10	q25	q50	q75	q90
FVA	0.1003223 (0.597)	0.2523418 * (0.064)	−0.2796101 (0.410)	−0.124194 (0.643)	0.0138709 (0.947)	0.2782729 * (0.056)	0.5454573 *** (0.002)
FI	11.04154 ** (0.022)	4.257766 (0.220)	4.630936 (0.610)	7.253274 (0.312)	9.582845 * (0.087)	14.0441 *** (0.000)	18.55231 *** (0.000)
FVA × FI	−0.3877637 (0.172)	−0.3174853 (0.120)	0.0902505 (0.863)	−0.1052872 (0.798)	−0.2789944 (0.387)	−0.6116533 *** (0.005)	−0.9478128 *** (0.000)
GDP	0.0002631 *** (0.003)	0.0000768 (0.228)	0.0001474 (0.369)	0.0001947 (0.133)	0.0002367 ** (0.019)	0.0003172 *** (0.000)	0.0003986 *** (0.000)
Trade	0.0348431 (0.127)	−0.0088431 (0.590)	0.0481575 (0.269)	0.0427111 (0.215)	0.0378727 (0.160)	0.028607 * (0.093)	0.0192438 (0.360)
Urban	−0.0153548 (0.655)	0.0052516 (0.832)	−0.0232617 (0.724)	−0.0200273 (0.701)	−0.017154 (0.673)	−0.0116514 (0.648)	−0.0060909 (0.847)

Note: Authors' computations. ***, **, and * 1%, 5%, and 10% levels of significance, respectively.

Table 8. Baseline MMQR Results: GVC Model.

Variables	Location	Scale	q10	q25	q50	q75	q90
GVC	−0.088503 * (0.093)	0.0333284 (0.451)	−0.1336764 *** (0.003)	−0.120571 *** (0.002)	−0.1025494 ** (0.015)	−0.0798476 (0.193)	−0.0290411 (0.811)
FI	−10.8532 ** (0.017)	3.73496 (0.328)	−15.9156 *** (0.000)	−14.4469 *** (0.000)	−12.4273 *** (0.001)	−9.88328 * (0.063)	−4.18962 (0.689)
GVC × FI	0.36080 *** (0.001)	−0.10772 (0.246)	0.50681 *** (0.000)	0.46445 *** (0.000)	0.40620 *** (0.000)	0.33282 ** (0.011)	0.16861 (0.508)
GDP	0.00034 *** (0.000)	0.00002 (0.493)	0.00031 *** (0.000)	0.00032 *** (0.000)	0.000336 *** (0.000)	0.00035 *** (0.000)	0.00038 *** (0.000)
Trade	−0.0061 (0.534)	0.02119 ** (0.011)	−0.03488 *** (0.000)	−0.02655 *** (0.000)	−0.01509 ** (0.051)	−0.00065 (0.959)	0.03165 (0.169)
Urban	0.00346 (0.857)	0.01190 (0.462)	−0.01267 (0.448)	−0.00799 (0.575)	−0.00155 (0.920)	0.00655 (0.772)	0.02470 (0.578)

Note: Authors' computations. ***, **, and * 1%, 5%, and 10% levels of significance, respectively.

Turning first to forward GVC participation (DVX), Table 6 reveals a consistently negative and statistically significant association between DVX and CO₂ emissions across all estimated quantiles. The coefficient remains negative from q10 to q90, ranging from −0.1459 at the lower quantile to −0.2597 at the highest quantile. This pattern indicates that countries with greater forward participation in global production networks tend to exhibit lower CO₂ emissions, conditional on the other explanatory variables included in the model.

In addition, the magnitude of the estimated coefficient increases gradually across the distribution, suggesting that the negative association between forward GVC participation and CO₂ emissions is stronger among countries located at higher emission levels. Such heterogeneity suggests that the environmental implications of forward participation depend on countries' positions within global production networks and their structural characteristics rather than being uniform across economies.

From an economic perspective, this finding may be consistent with productivity- and technology-related mechanisms associated with upstream integration into GVCs. Forward participation reflects the capacity of domestic industries to provide intermediate inputs incorporated into international production processes. In this context, participation in global networks may be accompanied by knowledge diffusion, improved production standards, and efficiency gains that can contribute to lower emission intensity (Shi & Yang, 2025). However, these mechanisms are not directly observed in the present framework; therefore, the estimated coefficients should be interpreted as conditional associations rather than evidence of a direct causal environmental effect.

Furthermore, the stronger negative association observed at higher emission quantiles may reflect differences in countries' production structures, technological capabilities, and absorptive capacities. Economies with initially higher emission levels may have greater scope for improving environmental performance through productivity improvements, technological upgrading, and more efficient resource utilization. Conversely, the weaker coefficients observed at lower quantiles suggest that countries already characterized by relatively low emission levels may have less room for additional environmental improvements associated with forward GVC integration.

These findings show that the environmental relationship between forward GVC participation and CO₂ emissions varies across emission levels. They also highlight the importance of country-specific conditions, including technological capacity, institutional quality, and the ability to benefit from international knowledge spillovers, in shaping the environmental implications of GVC integration (C. Liu & Zhao, 2021).

Turning to backward GVC participation (FVA), Table 7 reveals a markedly different pattern. The estimated coefficients vary considerably across the conditional distribution of CO₂ emissions, indicating that the environmental relationship associated with downstream integration is not uniform across countries. At lower emission levels (q10–q25), the FVA coefficients are negative but statistically insignificant, indicating no significant association with CO₂ emissions among countries located at the lower end of the emissions distribution. At the median quantile, the coefficient also remains statistically insignificant, suggesting a limited association between downstream GVC integration and emissions for countries characterized by intermediate emission levels.

By contrast, the relationship changes at higher quantiles. The FVA coefficient becomes positive and statistically significant at q75 and q90, reaching 0.2783 and 0.5455, respectively. Thus, higher levels of backward GVC participation are associated with greater CO₂ emissions among countries located in the upper part of the emissions distribution. The increasing magnitude of the coefficient across higher quantiles further suggests that the environmental pressures linked to downstream integration become more pronounced in economies characterized by higher emission levels.

This finding may be explained by the nature of backward participation, which involves the integration of foreign intermediate inputs into domestic production processes. In countries where industrial activities remain relatively energy-intensive and environmental upgrading capabilities are limited, deeper downstream integration may be accompanied by additional production pressures. This interpretation should be viewed as a possible mechanism rather than a direct causal channel, since the MMQR estimates capture conditional associations rather than structural causal effects. More broadly, the heterogeneity observed across quantiles highlights the importance of national conditions in shaping the environmental implications of backward GVC participation. Differences in technological capabilities, institutional quality, environmental regulations, and innovation capacity may influence countries' ability to transform GVC integration into more sustainable production structures (Demiral & Demiral, 2023). Economies with stronger innovation systems and more effective environmental governance may be better positioned to adopt cleaner technologies and improve production efficiency, thereby reducing the environmental pressures associated with downstream activities (Shi & Yang, 2025).

Comparing the two forms of participation provides further evidence of their distinct environmental patterns. While forward participation (DVX) is negatively associated with CO₂ emissions across the distribution, backward participation shows positive associations only among high-emission economies. This difference may reflect the distinct roles occupied by countries within global production networks: upstream activities may benefit more from knowledge and efficiency spillovers, whereas downstream activities may generate stronger production pressures when sustainable upgrading capacities remain insufficient.

This evidence is consistent with recent studies emphasizing that the environmental consequences of GVC integration depend on the type of participation, the position of countries within global production networks, and their ability to capture technological and institutional benefits (Veeramani & Manish, 2025). Therefore, the environmental implications of GVC participation should be interpreted within the broader context of countries' structural characteristics and development trajectories rather than as a homogeneous effect across economies.

Beyond these disaggregated measures, Table 8 reports the estimates for aggregate GVC participation. The findings provide further evidence that the relationship between global integration and CO₂ emissions varies across the conditional distribution. Unlike the disaggregated measures of GVC participation, which capture specific dimensions of

integration, the aggregate index reflects the combined effect of forward and backward participation within global production networks.

The estimated coefficients show a negative and statistically significant association between aggregate GVC participation and CO₂ emissions at the lower and middle quantiles. More specifically, the coefficients remain negative and significant from q10 to q50, ranging from -0.1337 at q10 to -0.1025 at q50. Accordingly, countries located in the lower and median parts of the emissions distribution tend to exhibit lower CO₂ emissions when they are more integrated into global value chains, conditional on the other factors included in the model.

At higher quantiles, however, this relationship weakens. The coefficients at q75 and q90 remain negative but lose statistical significance, suggesting that the association between aggregate GVC participation and lower emissions is less evident among countries characterized by higher emission levels. This variation across quantiles reinforces the view that the environmental implications of global integration are not identical across economies and may depend on their initial environmental conditions and structural characteristics.

The observed negative association in the lower and middle parts of the distribution may be consistent with several mechanisms identified in the GVC literature. Greater integration into international production networks can be accompanied by access to advanced production methods, knowledge spillovers, and efficiency improvements that may reduce emission intensity. Importantly, since these channels are not directly measured in the empirical model, the estimated coefficients should be interpreted as conditional relationships rather than evidence of a direct causal environmental effect.

Conversely, the absence of significant coefficients at higher emission quantiles suggests that the potential environmental advantages associated with GVC integration may depend on countries' capacity to transform global connectivity into sustainable production outcomes. Economies facing persistent carbon-intensive production structures, limited technological capabilities, or weaker environmental governance may encounter greater difficulties in capturing the potential environmental gains associated with international integration.

Such heterogeneity is consistent with recent studies emphasizing that the environmental consequences of GVC participation depend on countries' positions within global production networks and their ability to benefit from technological and knowledge spillovers (Gedefie & Wu, 2026). In particular, the sustainability implications of GVC integration are likely to be influenced by complementary factors such as innovation capacity, institutional quality, and environmental regulation (Doryń & Wawrzyniak, 2024).

Overall, the aggregate GVC estimates confirm that global integration is not associated with a uniform environmental outcome across countries. Instead, the relationship varies according to emission levels and national capabilities, highlighting the importance of considering heterogeneity when assessing the environmental dimension of globalization.

Turning to financial inclusion, the MMQR estimates reveal substantial heterogeneity across emission levels and GVC specifications. Rather than exhibiting a uniform environmental pattern, the estimated coefficients suggest that the role of financial inclusion depends on countries' production characteristics, their position within global value chains, and the allocation of financial resources.

In the DVX specification, financial inclusion displays a negative and statistically significant association with CO₂ emissions across all quantiles. The magnitude of the coefficient increases gradually from -5.398 at q10 to -20.290 at q90, indicating that the negative association between financial inclusion and CO₂ emissions becomes stronger among countries located in the upper part of the emissions distribution. This finding suggests that broader access to formal financial services may be associated with improved

environmental performance, particularly in economies where financial access can facilitate investment capacity, technological upgrading, and more efficient production processes.

Nevertheless, these results should not be interpreted as evidence that financial inclusion directly causes emission reductions. The observed relationship may reflect the interaction between financial development, firms' investment opportunities, technological capabilities, and institutional conditions that determine how financial resources are allocated.

A contrasting pattern emerges in the FVA specification. Financial inclusion coefficients are positive but statistically insignificant at lower quantiles, becoming positive and statistically significant at the median and upper quantiles. Specifically, the coefficient increases from 9.583 at q50 to 18.552 at q90. Hence, among countries characterized by higher emission levels and stronger backward participation in GVCs, greater financial inclusion is associated with higher CO₂ emissions.

This pattern may arise when downstream GVC activities remain concentrated in energy-intensive sectors, as improved access to finance may support production expansion and industrial investment without necessarily being accompanied by sufficient environmental upgrading. In such contexts, financial resources may continue to flow toward activities with relatively high carbon intensity. Nevertheless, this interpretation represents a potential mechanism rather than a direct causal explanation of the estimated relationship.

The aggregate GVC specification presents yet another pattern. Financial inclusion exhibits a negative and statistically significant association with CO₂ emissions from q10 to q75, while the coefficient becomes statistically insignificant at q90. Accordingly, the environmental association of financial inclusion is generally favorable across most of the emission distribution but becomes weaker among the highest-emission economies.

Taken together, these differences point to two potential mechanisms. On the one hand, financial inclusion can be associated with improved environmental performance by reducing financing constraints, facilitating access to cleaner technologies, and supporting investments compatible with sustainable production processes (Abbas et al., 2024). On the other hand, when financial resources are primarily directed toward carbon-intensive activities or rapid industrial expansion, greater financial access may coincide with additional environmental pressures (Akisik, 2024).

These findings imply that the environmental dimension of financial inclusion should be understood as conditional on the economic environment in which financial resources are mobilized. Expanding access to finance alone may not be sufficient to generate sustainable outcomes; its environmental implications also depend on technological capacity, sectoral composition, institutional quality, and the ability of financial systems to support environmentally oriented investments.

The interaction terms provide further insights into how the relationship between GVC participation and CO₂ emissions varies according to financial development conditions. Tables 6–8 indicate that the moderating role of financial inclusion is not homogeneous but depends on the type of GVC participation considered and the position of countries within the conditional distribution of emissions.

Following Brambor et al. (2006), the interpretation of interaction effects is based on the conditional marginal effect of GVC participation rather than on the interaction coefficient alone. Accordingly, the estimated interaction terms indicate whether the association between GVC participation and CO₂ emissions changes with the level of financial inclusion.

For forward GVC participation (DVX), the interaction coefficient is positive and statistically significant across all quantiles. Its magnitude increases from 0.491 at q10 to 0.838 at q90, indicating that higher levels of financial inclusion are associated with a stronger positive interaction between DVX participation and CO₂ emissions.

Economically, this pattern may indicate that in economies where forward integration is accompanied by greater financial access, expanded financing opportunities may coincide with stronger production and investment activities linked to participation in international production networks. Although financial inclusion can facilitate technological upgrading and efficiency improvements, its environmental association depends on whether financial resources are directed toward sustainable activities or toward production expansion in relatively carbon-intensive sectors.

By contrast, the interaction pattern for backward GVC participation (FVA) shows a different configuration. The coefficients are statistically insignificant at lower and median quantiles but become negative and significant at higher quantiles, reaching -0.612 at q75 and -0.948 at q90. This pattern suggests that financial inclusion is associated with a weaker positive relationship between backward participation and CO₂ emissions among countries located at the upper end of the emission distribution.

In high-emission economies, this may reflect greater capacity to use financial resources for technological upgrading, production efficiency improvements, and adaptation to environmental standards within downstream GVC activities. However, this mechanism should be interpreted cautiously, as the MMQR framework identifies conditional relationships rather than direct causal channels.

Finally, for the aggregate GVC specification, the interaction term is positive and statistically significant from q10 to q75 but becomes insignificant at q90. Thus, financial inclusion strengthens the association between overall GVC integration and CO₂ emissions among countries located in the lower and middle parts of the emissions distribution, whereas this moderating relationship becomes weaker among the highest-emission economies.

Overall, the contrasting interaction patterns across DVX, FVA, and aggregate GVC participation demonstrate that financial inclusion does not have a single environmental role. Its association with emissions depends on how countries participate in global production networks, the structure of domestic production, and their ability to channel financial resources toward environmentally sustainable activities.

From this perspective, expanding access to finance alone may not automatically generate environmental improvements. The environmental contribution of financial inclusion appears to depend on complementary factors, including financial allocation mechanisms, technological capabilities, institutional quality, and the orientation of investment toward cleaner production systems.

Finally, the control variables provide further insights into the determinants of CO₂ emissions across the conditional distribution. GDP per capita exhibits a positive and statistically significant association with CO₂ emissions in most specifications and across a large part of the conditional distribution (Chindo et al., 2015). This pattern is consistent with the scale effect of economic activity, whereby higher production levels are generally associated with greater energy demand and environmental pressure. At the same time, the heterogeneous magnitude of the coefficients across quantiles indicates that the environmental implications of economic development vary according to countries' structural characteristics.

Trade openness also exhibits heterogeneous associations across specifications. In the DVX model, it is positively associated with CO₂ emissions at higher quantiles, suggesting that stronger international integration may coincide with additional environmental pressures in high-emission economies (Wen et al., 2020). In contrast, the aggregate GVC model shows a negative association at lower and median quantiles, which may reflect efficiency gains, specialization effects, and access to cleaner production practices (B. Li & Haneklaus, 2022). Overall, these findings indicate that the environmental implications of trade openness vary according to how countries are integrated into global markets.

Regarding urbanization, no systematic association with CO₂ emissions emerges across the estimated models. Its coefficient becomes positive and significant only at the highest quantile in the DVX specification, while remaining insignificant in the FVA and aggregate GVC models. This evidence suggests that the environmental implications of urbanization depend on complementary factors such as urban planning, infrastructure quality, and the capacity to implement sustainable urban strategies (Ngono et al., 2025).

4.3. Conditional Marginal Effects of Financial Inclusion

Consistent with the approach proposed by Brambor et al. (2006), Table 9 and Figure 2 present the conditional marginal effects of GVC participation on CO₂ emissions across different levels of financial inclusion. Unlike the interaction coefficients reported in the base-line MMQR models, conditional marginal effects provide a more meaningful interpretation of the moderating role of financial inclusion by showing how the association between GVC participation and CO₂ emissions changes across the observed range of financial inclusion.

Table 9. Conditional Marginal Effects of GVC Participation on CO₂ Emissions across Different Levels of Financial Inclusion (MMQR, Median Quantile q50).

Financial Inclusion (FI)	DVX	FVA	GVC
0.0	−0.2179 *** (0.0441)	0.0719 (0.1962)	−0.1572 *** (0.0432)
0.1	−0.1489 *** (0.0378)	0.0316 (0.1694)	−0.1133 *** (0.0350)
0.2	−0.0799 ** (0.0321)	−0.0086 (0.1439)	−0.0695 ** (0.0284)
0.3	−0.0109 (0.0271)	−0.0488 (0.1205)	−0.0256 (0.0250)
0.4	0.0581 ** (0.0234)	−0.0890 (0.1007)	0.0182 (0.0260)
0.5	0.1271 *** (0.0218)	−0.1292 (0.0869)	0.0621 ** (0.0309)
0.6	0.1961 *** (0.0226)	−0.1694 * (0.0823)	0.1059 *** (0.0383)
0.7	0.2651 *** (0.0256)	−0.2096 ** (0.0883)	0.1498 *** (0.0470)
0.8	0.3341 *** (0.0301)	−0.2498 ** (0.1030)	0.1936 *** (0.0565)
0.9	0.4032 *** (0.0357)	−0.2900 ** (0.1234)	0.2375 *** (0.0663)
1.0	0.4722 *** (0.0418)	−0.3303 ** (0.1472)	0.2813 *** (0.0764)

Notes: The conditional marginal effects are computed as: $\frac{dCO_{2,t}}{dGVC_{i,t}} = \beta_1 + \beta_3 FI_{i,t}$, using the median MMQR (q50) estimates following Brambor et al. (2006). Standard errors are reported in parentheses. ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively.

For the DVX specification, the marginal effect varies across financial inclusion levels. At relatively low levels of FI ($FI \leq 0.2$), forward GVC participation is negatively and significantly associated with CO₂ emissions. The effect becomes statistically insignificant around $FI = 0.3$ and turns positive and significant from approximately $FI = 0.4$ onwards. This pattern indicates that the relationship between forward GVC participation and emissions depends on financial inclusion levels: at lower levels of financial inclusion, DVX participation is associated with lower emissions, whereas at higher levels of financial inclusion, the association becomes positive. This apparent change in sign does not necessarily contradict the main DVX result but reflects the moderating role of financial inclusion. At lower levels of FI, forward GVC participation may be associated with technological upgrading and efficiency gains, which are consistent with lower CO₂ emissions (Abbas et al., 2024). As financial inclusion increases, however, greater access to finance may facilitate additional investment, production, and export activities. If these financial resources are not sufficiently directed toward cleaner technologies and low-carbon activities, the resulting expansion in economic activity may outweigh the initial efficiency gains, making the marginal effect of DVX positive (Ha & Nguyen, 2025). This interpretation aligns with recent evidence showing that the environmental implications of financial inclusion vary according to how financial resources are allocated and the broader structural and institutional context in which financial deepening occurs (Nguyen, 2026).

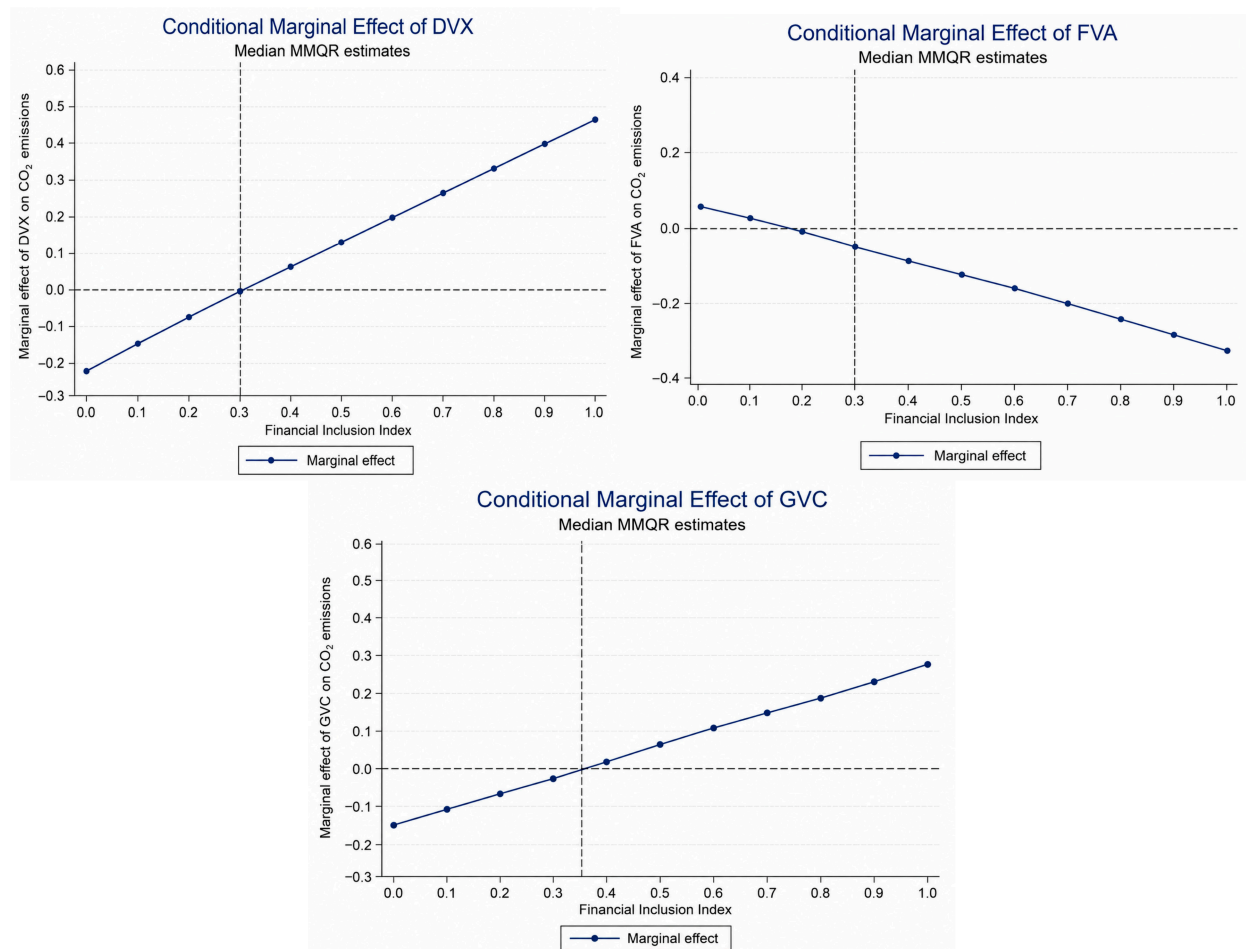


Figure 2. Conditional Marginal Effects of DVX, FVA, and GVC on CO₂ Emissions across Different Levels of Financial Inclusion (MMQR q50).

The FVA specification displays a different pattern. The marginal effect is statistically insignificant at low and medium levels of financial inclusion but becomes negative and statistically significant when FI exceeds approximately 0.6. This result suggests that higher levels of financial inclusion are associated with lower environmental pressure linked to backward GVC participation, particularly in countries with relatively high financial inclusion. This relationship may be consistent with the possibility that improved financial access facilitates productivity improvements, technological upgrading, and more efficient production processes within downstream activities.

The aggregate GVC specification presents a pattern closer to that observed for DVX. The marginal effect is initially negative at low levels of financial inclusion, becomes statistically insignificant around FI = 0.3–0.4, and turns positive and significant from approximately FI = 0.5 onwards. This suggests that the environmental association of overall GVC integration varies according to the degree of financial inclusion.

The conditional marginal effects therefore show that the relationship between GVC participation and CO₂ emissions varies with the level of financial inclusion and differs across forms of GVC participation. This evidence highlights the importance of considering financial development conditions when assessing the environmental implications of global value chain integration.

4.4. Inter-Quantile Equality Test

To examine whether the estimated MMQR coefficients differ significantly across the conditional distribution of CO₂ emissions, post-estimation Wald tests of inter-quantile

coefficient equality are conducted based on [Koenker and Bassett \(1982\)](#). These tests complement the MMQR estimates by providing statistical evidence on whether the differences observed across quantiles represent significant distributional heterogeneity.

Consistent with the empirical strategy adopted by [Erol and Dogan \(2024\)](#), the null hypothesis of coefficient equality is tested jointly across the five estimated quantiles (q10, q25, q50, q75, and q90). In addition, pairwise Wald tests comparing the lower and upper tails of the distribution (q10 versus q90) are performed to determine whether the estimated effects differ between countries characterized by relatively low and high CO₂ emissions.

The tests are implemented as post-estimation Wald restrictions on the MMQR coefficients. Table 10 reports the findings and provides further evidence on the heterogeneity identified in the baseline estimations.

Table 10. Tests of Inter-Quantile Coefficient Equality.

Model	Variable	Global Wald $\chi^2(4)$	<i>p</i> -Value	q10 vs. q90 $\chi^2(1)$	<i>p</i> -Value
Model DVX	DVX	18.47 ***	0.0010	8.56 ***	0.0034
	FI	22.34 ***	0.0002	14.12 ***	0.0002
	DVX $\times$ FI	15.89 **	0.0032	7.98 ***	0.0047
Model FVA	FVA	14.23 *	0.0066	9.45 ***	0.0021
	FI	12.87 **	0.0120	7.23 ***	0.0072
	FVA $\times$ FI	11.54 **	0.0211	6.89 ***	0.0087
Model GVC	GVC	2.89	0.5760	1.45	0.2286
	FI	16.78 **	0.0021	11.23 ***	0.0008
	GVC $\times$ FI	3.45	0.4850	2.10	0.1473

Notes: ***, ** and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Source: Authors' calculations.

For the DVX specification, the global Wald tests reject the hypothesis of coefficient equality for forward GVC participation, financial inclusion, and their interaction term. The q10–q90 comparisons also reveal significant differences between the lower and upper parts of the emission distribution. This evidence supports the heterogeneity observed in the MMQR estimates, showing that the association between forward GVC participation, financial inclusion, and CO₂ emissions varies across emission levels.

A similar result emerges for the FVA specification, with significant inter-quantile differences for backward GVC participation, financial inclusion, and the interaction term. The rejection of coefficient equality indicates that the environmental association of downstream GVC integration is not constant across countries but varies with their position within the CO₂ emission distribution.

The aggregate GVC specification, however, yields a different result. The equality hypothesis cannot be rejected for the GVC coefficient or the GVC $\times$ FI interaction term, suggesting that the overall GVC index does not display statistically significant variation across quantiles. Financial inclusion continues to exhibit significant heterogeneity across the emission distribution, suggesting that while the aggregate measure of GVC participation captures a relatively stable relationship, the role of financial inclusion varies across emission levels.

These findings underline the importance of distinguishing between different dimensions of GVC participation. The aggregate GVC indicator may conceal the heterogeneous relationships identified for forward and backward participation, reinforcing the relevance of analysing these two components separately. The inter-quantile tests thus provide formal statistical support for the distributional heterogeneity identified by the MMQR estimates and show why mean-based estimators may overlook important differences across emission levels.

4.5. Robustness and Additional Analysis

To examine the robustness of the baseline MMQR results, additional estimations are conducted using Fixed Effects (FE), System Generalized Method of Moments (System-GMM), and Common Correlated Effects Mean Group (CCEMG) estimators. These alternative approaches address complementary econometric issues, including unobserved country-specific characteristics, potential endogeneity concerns, and cross-sectional dependence (Arellano & Bover, 1995; Blundell & Bond, 1998; Pesaran, 2006). As reported in Table 11, the main relationships identified by MMQR remain broadly consistent across these alternative estimators.

Table 11. Robustness Results.

Variables	Model 1			Model 2			Model 3		
	FE	GMM	CCEMG	FE	GMM	CCEMG	FE	GMM	CCEMG
DVX	−0.185 ** (0.031)	−0.174 *** (0.012)	−0.201 ** (0.026)						
FVA				0.125 ** (0.045)	0.108 ** (0.031)	0.142 ** (0.022)			
GVC							−0.095 ** (0.032)	−0.108 *** (0.004)	−0.087 ** (0.018)
FI	−10.872 *** (0.000)	−11.245 *** (0.000)	−10.634 *** (0.001)	10.85 *** (0.001)	11.24 *** (0.000)	10.62 *** (0.002)	−11.20 *** (0.000)	−12.10 *** (0.000)	−10.75 *** (0.001)
DVX × FI	0.621 *** (0.000)	0.587 *** (0.001)	0.654 *** (0.000)						
FVA × FI				−0.315 *** (0.001)	−0.342 *** (0.000)	−0.298 *** (0.004)			
GVC × FI							0.380 *** (0.001)	0.425 *** (0.000)	0.395 *** (0.002)
GDP	0.00021 *** (0.000)	0.0002 *** (0.001)	0.00024 *** (0.000)	0.00024 *** (0.000)	0.00022 *** (0.001)	0.00025 *** (0.000)	0.00034 *** (0.000)	0.00036 *** (0.001)	0.00033 *** (0.000)
Trade	0.024 *** (0.001)	0.022 ** (0.013)	0.028 *** (0.000)	0.035 ** (0.012)	0.039 ** (0.018)	0.031 ** (0.009)	−0.008 (0.42)	−0.012 ** (0.04)	−0.006 (0.35)
Urban	0.015 (0.210)	0.018 (0.184)	0.012 (0.290)	−0.014 (0.30)	−0.012 (0.40)	−0.016 (0.25)	0.004 (0.75)	0.003 (0.80)	0.005 (0.65)
Instruments		27			27			27	
AR(1)		0.046			0.030			0.042	
AR(2)		0.573			0.610			0.618	
Hansen test		0.492			0.612			0.354	

Note: Authors' computations. *** and ** denote 1% and 5% levels of significance, respectively.

Regarding the different dimensions of GVC participation, forward participation (DVX) remains negatively associated with CO₂ emissions across FE, System-GMM, and CCEMG estimations, whereas backward participation (FVA) exhibits a positive association with emissions. The aggregate GVC indicator continues to display a negative relationship with CO₂ emissions. This consistency across estimators supports the view that the environmental association of GVC participation varies according to the specific form of integration within global production networks.

Financial inclusion also exhibits distinct associations across the three GVC specifications. It remains negatively associated with CO₂ emissions in the DVX and aggregate GVC models, while exhibiting a positive association in the FVA specification. These differences indicate that the environmental relationship of financial inclusion depends on the productive context in which financial resources are mobilized. Financial access may be associated

with improved efficiency and technological upgrading in some contexts, whereas it may coincide with stronger production expansion in carbon-intensive activities in others.

The interaction terms provide further support for the moderating role of financial inclusion and remain statistically significant across the alternative estimators. The positive $DVX \times FI$ and $GVC \times FI$ coefficients indicate that higher levels of financial inclusion are associated with a stronger relationship between GVC participation and CO₂ emissions in these specifications. In the FVA specification, the negative $FVA \times FI$ coefficient suggests that greater financial inclusion is associated with a weaker positive relationship between backward GVC participation and emissions. Hence, the moderating role of financial inclusion varies with the type of GVC participation considered.

Among the control variables, GDP per capita remains positively associated with CO₂ emissions across the three specifications, supporting the relevance of the economic scale effect in explaining environmental pressures. Trade openness exhibits heterogeneous associations across models, while urbanization remains statistically insignificant, suggesting that its environmental association depends on broader structural conditions.

The diagnostic tests for the System-GMM models further support the reliability of these estimations. The Hansen test does not reject the null hypothesis of instrument validity, while the AR(2) tests indicate the absence of second-order serial correlation (Hansen & Singleton, 1982). The agreement of the main findings across MMQR, FE, System-GMM, and CCEMG therefore strengthens the robustness of the empirical evidence.

Despite this consistency across estimators, MMQR remains the main specification because the central objective of the study is to capture heterogeneity in the relationships between GVC participation, financial inclusion, and CO₂ emissions across the conditional emission distribution. The alternative estimations serve as complementary robustness checks by addressing additional econometric concerns related to unobserved heterogeneity, endogeneity, and cross-sectional dependence.

5. Conclusions and Policy Implications

This study examines the relationship between Global Value Chain (GVC) participation, financial inclusion, and CO₂ emissions using a balanced panel of 41 developed and emerging economies over the period 2004–2022. Using the Method of Moments Quantile Regression (MMQR), complemented by Fixed Effects, System-GMM, and Common Correlated Effects Mean Group (CCEMG) estimations, the analysis moves beyond average effects and provides evidence on how these relationships vary across different levels of environmental pressure.

The empirical results reveal substantial heterogeneity in the environmental association of GVC participation, depending on the type of integration and countries' positions within the CO₂ emission distribution. Forward participation (DVX) is negatively associated with emissions across the conditional distribution, with stronger relationships observed among higher-emission economies. This finding may reflect productivity improvements, technological upgrading, and knowledge diffusion associated with upstream integration. However, these mechanisms should be interpreted as potential channels rather than direct causal effects.

Backward participation (FVA), however, shows a different relationship. While no significant association is observed at lower and medium quantiles, backward participation becomes positively associated with CO₂ emissions among higher-emission economies. Such a relationship may reflect additional environmental pressures from downstream integration in contexts where production structures remain relatively carbon-intensive and sustainable upgrading capacities are limited. Meanwhile, the aggregate GVC indicator provides an intermediate picture, showing a negative association at lower and median quantiles but

weaker relationships at higher emission levels. This comparison shows that aggregate measures of GVC participation may conceal important differences between forward and backward integration.

Financial inclusion also plays a context-dependent role. It is negatively associated with CO₂ emissions in the DVX and aggregate GVC specifications, whereas a positive association emerges in the FVA model, particularly among higher-emission economies. These differences indicate that the environmental dimension of financial inclusion depends on the sectors and activities supported by financial resources. Access to finance may be associated with efficiency improvements and technological upgrading when resources are directed toward sustainable activities, while it may coincide with stronger environmental pressures when financing supports carbon-intensive expansion.

The interaction analysis provides further evidence of this conditional role. The marginal effects indicate that the association between GVC participation and CO₂ emissions changes across different levels of financial inclusion and varies according to the form of GVC integration. Financial inclusion therefore does not have a uniform environmental association; its implications vary with financial allocation mechanisms, productive structures, and countries' capacity to use financial resources for sustainable transformation.

These findings contribute to the literature by demonstrating that the globalization–environment nexus cannot be fully understood through aggregate indicators of international integration. By distinguishing between forward, backward, and overall GVC participation and incorporating financial inclusion as a moderating factor, the analysis reveals heterogeneous relationships across the conditional emission distribution that may remain hidden under conventional mean-based estimations. More broadly, the evidence emphasizes the role of countries' structural characteristics, technological capabilities, and institutional capacity in shaping the environmental implications of global integration.

Several policy implications emerge from these findings. Policymakers should consider the specific position of countries within global value chains when designing industrial and environmental strategies. Promoting higher value-added activities, technological upgrading, and knowledge-intensive integration may support more environmentally sustainable participation in global production networks, while excessive reliance on carbon-intensive downstream activities may increase environmental challenges.

Financial inclusion policies should also be aligned with sustainability objectives. Expanding access to financial services should be complemented by mechanisms that encourage green investment, cleaner technologies, and environmentally oriented financing. The evidence indicates that broader financial access alone is not necessarily associated with better environmental outcomes. Its contribution depends on how financial resources are allocated across economic activities.

In addition, trade and industrial policies should incorporate environmental considerations by encouraging sustainable supply chains, strengthening environmental standards, and improving institutional capacities that facilitate cleaner production processes. Countries seeking deeper integration into global markets should therefore combine openness strategies with environmental and technological upgrading policies.

Despite its contributions, the study is subject to several limitations. Data availability prevents the inclusion of some potentially relevant dimensions, such as environmental regulation, renewable energy deployment, and green innovation indicators. Another limitation concerns the measurement of financial inclusion. The FI index is constructed using ATMs and commercial bank branches per 100,000 adults as indicators of formal financial access, providing consistent coverage across the 41 countries over the 2004–2022 period. However, these indicators primarily capture the physical-access dimension of financial inclusion and do not fully reflect its multidimensional nature. In particular,

digital financial services, mobile banking, credit access, fintech development, and usage-based dimensions could not be incorporated because comparable data are not consistently available across countries and over the entire sample period. Finally, although MMQR captures heterogeneous relationships across emission levels, it does not fully identify differences related to institutional quality and environmental governance.

Further research could address these limitations by incorporating additional institutional and environmental variables, examining sector-specific GVC participation, and exploring the role of green innovation and environmental policies in shaping the globalization–financial inclusion–environment relationship. Broader measures of financial inclusion, particularly those capturing digital and usage-based dimensions, could also be considered as more comprehensive and harmonized cross-country data become available. These extensions could provide deeper insights into the conditions that support more sustainable integration into global production networks.

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Appendix A

Appendix A.1. List of Countries

The sample consists of the following countries:

Angola, Argentina, Belgium, Brazil, Brunei Darussalam, Bulgaria, Cambodia, Cameroon, Chile, China, Colombia, Costa Rica, Cyprus, Denmark, Finland, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Jordan, Malaysia, Malta, Mexico, Morocco, Pakistan, Peru, Philippines, Portugal, Romania, Saudi Arabia, South Africa, Spain, Sweden, Switzerland, Thailand, Ukraine, United Arab Emirates.

Appendix A.2. PCA Results for Financial Inclusion Index

Component	Eigenvalue	Proportion	Cumulative
Comp1	1.82602	0.9130	0.9130
Comp2	0.173983	0.0870	1.0000

Principal Component Loadings for the Financial Inclusion Index.

Indicator	Comp1	Comp2
ATMs	0.7071	0.7071
Commercial bank branches	0.7071	−0.7071

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