Oeconomia
Copernicana

Volume 15 Issue 3 September 2024

p-ISSN 2083-1277, e-ISSN 2353-1827

www.oeconomia.pl

ORIGINAL ARTICLE

Citation: Doryń, W., & Wawrzyniak, D. (2024). Tracing the impact of global value chain participation on CO_2 emissions under the technology gap heterogeneity: Evidence from emerging and developing countries. *Oeconomia Copernicana*, *15*(3), 957–989. https://doi.org/10.24136/oc.2717

Contact to corresponding author: Wirginia Doryń, wirginia.doryn@uni.lodz.pl

Article history: Received: 25.10.2023; Accepted: 29.08.2024; Published online: 30.09.2024

Wirginia Doryń
University of Lodz, Poland
orcid.org/0000-0001-7112-4295

Dorota Wawrzyniak
University of Lodz, Poland
orcid.org/0000-0002-2829-3664

Tracing the impact of global value chain participation on CO_2 emissions under the technology gap heterogeneity: Evidence from emerging and developing countries

JEL Classification: *F18; Q53; Q56; O44*

Keywords: *carbon dioxide emission; global value chain (GVC); technology gap; environmental Kuznets curve (EKC); emerging and developing countries*

Abstract

Research background: The issue of carbon dioxide (CO_2) emissions, recognized as one of the major drivers of environmental degradation, has attracted considerable attention from academic researchers, policymakers, and professionals in relevant fields. Based on the existing research, countries' pollution levels are shaped by a combination of factors, including their participation in global value chains (GVCs) and degree of technological advancement. Still,

relatively little is known about the mutual interdependence of these factors in determining CO_2 emissions, which creates the research gap that we address in this paper.
Purpose of the article: The aim of this study is to broaden understanding of the impact of GVC involvement on CO_2 emissions in emerging and developing countries. We examine the impact of GVC participation on CO_2 emissions conditional on a country's distance to the world's technological frontier. The rationale is that a country's technological advancement may underpin the environmental impact of GVC participation. We claim that the adoption of technology by less developed countries via GVCs is conditioned by their absorptive capacity, which is determined by their initial level of technological development.
Methods: To investigate this issue, we employ the Arellano-Bond generalized method of moments (GMM) estimator and four patent-based technology gap indicators. The utilized data cover 90 emerging and developing countries.
Findings & value added: Our study demonstrates that a country's technological advancement is the key factor that conditions the acquisition of environmental benefits of GVC participation. We find that countries with shorter distances to the world's technological frontier enjoy a decline in CO_2 emissions as their GVC involvement increases. At the same time, countries that are further away from the technological leader may not be able to experience CO_2 reduction with increased GVC integration due to their inadequate absorptive capacity, which hampers the environmental benefits related to technology diffusion through GVCs.

Introduction

Carbon dioxide (CO_2) emissions are constantly rising. According to World Bank data, the world's per-capita emissions of CO_2 in recent decades have returned to the historically high levels of the 1970s and 1980s, peaking at approx. 4.61 metric tons per capita in 2013.[1] Changes in global CO_2 emissions are particularly alarming given that the recent upward trend has been interrupted almost exclusively by global crises, rebounding sharply as economies recover. Historically, developed countries have contributed more to global CO_2 emissions and have experienced higher emissions in per capita terms. However, nowadays, it is developing nations that lead the growth rate of emissions (Borowiec & Papież, 2024). Therefore, the development trajectories of this group of countries are of crucial importance in mitigating global air pollution.

Previous studies analysed numerous drivers of CO_2 emissions, including economic growth (Dong *et al.*, 2020; Farooq *et al.*, 2023; Zmami & Ben-Salha, 2020), the industrial structure of the economy (Azam *et al.*, 2022; Patel & Mehta, 2023; Wu *et al.*, 2021), foreign direct investment (Mert & Caglar, 2020; Uche *et al.*, 2023; Zmami & Ben-Salha, 2020), foreign trade

[1] https://data.worldbank.org/indicator/EN.ATM.CO2E.PC, accessed on 06.09.2021.

(Umar *et al.*, 2023; Wang *et al.*, 2023; Zmami & Ben-Salha, 2020), financial development (Ofori *et al.*, 2023; Singhania & Saini, 2021; Yasin *et al.*, 2021), urbanisation (Azam *et al.*, 2022; Yasin *et al.*, 2021; Zmami & Ben-Salha, 2020), quality of institutions (Haldar & Sethi, 2021; Wawrzyniak & Doryń, 2020; Yasin *et al.*, 2021), digitalisation (Ali *et al.*, 2023; Avom *et al.*, 2020; Haini, 2021) and technology (Chen & Lee, 2020; Habiba *et al.*, 2022; Xin *et al.*, 2021).

This study contributes to a relatively recent strand of empirical literature that examines the effects of Global Value Chain (GVC) involvement on environmental pollution. Specifically, our study investigates the impact of GVC participation on CO_2 emissions in the particular setting of emerging and developing countries. The developmental trajectories of these countries are increasingly shaped by their integration into GVCs. Dividing the overall production process into smaller tasks has facilitated their access to foreign markets, allowing them to specialise in relatively simple tasks where they hold a comparative advantage without the need to build complete production capacities (Meng *et al.*, 2020). However, these countries, which are typically abundant in cheap, unskilled labour, often become locked into the tangible, low value-added stages of global value chains. These stages are typically characterised by high energy consumption, such as manufacturing and assembly. As a result, developing countries are heavily involved in highly polluting activities (Jin *et al.*, 2022; Yang & Liu, 2021). Meanwhile, developed countries, leveraging their comparative advantages in capital and technology, have secured their positions in intangible, high-value-added, “clean” (low-carbon-intensive) activities (e.g., R&D, brand management, marketing, and after-sales services) while outsourcing high-polluting production to developing countries (Jin *et al.*, 2022).

Other environmental consequences stem from technology transfer from advanced to less developed countries through GVCs (Antràs, 2020). The beneficial environmental impact of participating in GVCs arises from the environmentally demanding requirements, standards and regulations that domestic companies must comply with as a consequence of engaging in GVCs (Siewers *et al.*, 2024). Previous research also documented the productivity gains and/or energy efficiency improvements related to GVC participation (Agostino *et al.*, 2023; Rigo, 2021; Siewers *et al.*, 2024). Entering GVCs may enable firms from developing countries access to cleaner technologies (Rigo, 2021). However, the adoption of new technologies, in particular, climate-friendly ones, is far from automatic. On the contrary, the transfer and utilisation of new technology is dependent on a firm's absorptive capacity, i.e., its ability to internalise external knowledge (Gentile *et al.*, 2021; Morrison *et al.*, 2008). Gentile *et al*. (2021) argued that absorptive capacity at various levels, from individual firms to the entire economy, determines the impact of GVC-related knowledge on developing countries.

The results of previous empirical research on the carbon consequences of GVC participation remain ambiguous. Some studies found that it increases CO_2 emissions (e.g., Jin *et al.*, 2022 in a subsample of developing countries), while others suggest a reduction (e.g., Assamoi *et al.*, 2020; Jin *et al.*, 2022 in a subsample of developed countries). Meanwhile, some research indicates a curvilinear relationship (e.g., Ali *et al.*, 2023; Wang *et al.*, 2019). Other studies suggest that the impact differs between backward and forward GVC participation modes (e.g., Qian *et al.*, 2022) and may vary across industries (Wang *et al.*, 2022).

The present study contributes to the existing research by performing a more nuanced investigation of the impact of GVC participation on CO_2 emissions. We introduce a novel perspective on the GVC involvement-CO_2 emissions nexus and reconsider this relationship through the lens of technological advancement. We hypothesize and present empirical evidence that GVC participation alone does not necessarily lead to improvements in environmental quality in developing countries; rather, the relationship between GVC participation and CO_2 emissions may be conditional on the country's level of technology.

We expect that the possibility of experiencing the potential benefits related to participating in GVCs, i.e., the gains from access to clean technologies and managerial expertise of partners within the GVC production network, depends on the country's technological level as it conditions the adoption of new technologies and managerial practices. In other words, we believe that the exploitation of foreign sources of knowledge from within the value chain (its absorption and diffusion), which consequently translates into the technological upgrade of the recipient country, is conditional on its capabilities, i.e., its knowledge infrastructure (Fagerberg *et al.*, 2018; Gentile *et al.*, 2021). We proxy the technology gap with four patent-based indicators.

We add to the existing literature in several ways. First, we present original insights into the link between GVCs and environmental pollution. Our study is one of the relatively few analyses that consider the conditional impact of GVC participation on CO_2 emissions. Additionally, the estimation results are accompanied by a graphical representation of the marginal effects of GVC participation on CO_2 emissions as the technology gap changes. The inclusion of figures makes it possible to interpret these effects across the full range of a countries' technological advancement.

Second, while the existing research focused on different research objects such as particular economies (e.g., Germany in Chen *et al.*, 2021; Pakistan in Umar *et al.*, 2023; China in Yang & Liu, 2021) or groups of countries at varying stages of development (e.g., 11 Asian countries in Assamoi *et al.*, 2020; RCEP countries in Qian *et al.*, 2022; 62 countries and regions in Wang *et al.*, 2019), few studies consider the potential differences between developed and developing economies (e.g., Jin *et al.*, 2022; Wang *et al.*, 2021). Therefore, to address this shortcoming, the present study aims to deepen understanding of the impact of GVC participation on carbon emissions within the specific context of emerging and developing countries.

Third, we provide the foundation for developing theoretical models that describe the environmental consequences of GVC involvement in developing countries. We do this by exposing the mechanism that underlies the studied relationship.

In terms of methodology, this study adopts the generalized method of moments (GMM) estimation technique, which accounts for endogeneity issues. The utilised data cover 90 emerging and developing countries.

The paper is organised as follows: Section 2 reviews the literature. Section 3 describes the methodology and data. The empirical results are presented in Section 4, while the discussion is in Section 5. The last section concludes.

Literature review and hypotheses development

Scholars have not yet reached a consensus on the environmental effect of international trade (Wang *et al.*, 2019), despite numerous studies conducted in this field (e.g., Balsalobre-Lorente *et al.*, 2018; Burki & Tahir, 2022; Dauda *et al.*, 2021; Farooq *et al.*, 2023; Li & Haneklaus, 2022; Muhammad & Long, 2021; Nguyen *et al.*, 2021; Umar *et al.*, 2023; Wang *et al.*, 2023; Zmami & Ben-Salha, 2020).

One of the possible reasons for the mixed findings stems from the two opposing forces that determine the impact of a country's foreign trade engagement on environmental pollution. These forces correspond to the two hypotheses that explain the environmental impact of a country's participation in international trade. The first one is the "pollution haven hypothesis", which claims that multinational firms relocate their "dirty" activities to countries with relatively weak environmental standards. Consequently, pollution-intensive production is located in "pollution havens". The second is the "pollution halo" hypothesis, which holds that developing countries can reduce pollutant emissions thanks to the diffusion of clean technology and specialised management expertise from their developed trade partners (Yang & Liu, 2021; Singhania & Saini, 2021; Zmami & Ben-Salha, 2020).

Similarly, opposite forces are related to the three environmental effects of international trade: the scale effect, the technique effect and the composition effect (Ansari & Khan, 2021; Grossman & Krueger, 1991; Wu *et al.*, 2024). The scale effect implies an increase in pollution emissions resulting from expanding economic activity induced by foreign trade. The technique effect predicts a beneficial impact of trade on the environment as a consequence of improved technology and/or more stringent pollution policies. The composition effect assumes that countries specialise in goods and services according to their comparative advantage, which arises from their factor endowment (Twerefou *et al.*, 2019).

According to the factor endowment hypothesis, developed countries specialise in "dirty" capital-intensive production due to relative capital abundance, while developing countries produce relatively "clean" labour-intensive goods (Dietzenbacher & Yan, 2024). In turn, comparative advantages impact the economic structure of countries. In a developing country setting, the composition effect is likely to foster industrialisation and thereby increase pollution (Wang *et al.*, 2019). However, the actual effect of the specialisation pattern is dependent on the strength of a country's environmental policy, which is laxer in developing countries (Jin *et al.*, 2022).

The inconclusive results may also be attributed to different measures of foreign trade engagement and the fact that many previous studies that considered the environmental impact of international trade, in particular, the CO_2-trade relationship, neglected the GVC division system (Jin *et al.*, 2022; Wang *et al.*, 2019). Still, taking this factor into account did not provide a clear answer on its environmental consequences.

Wang *et al.* (2019) studied the CO_2 emissions-GVCs relationship using data from 62 countries and regions for the period 1995–2011. They employed fixed effect, random effect and mixed effect regressions and found an inverted U-shaped relationship. Higher GVC involvement contributed to higher CO_2 emissions per capita when the participation degree was lower than 29.59%. After reaching that point, higher GVC participation led to reduced CO_2 emissions. The study also evidenced that a higher share of R&D expenditures contributed to lowering CO_2 emissions per capita.

Jin *et al.* (2022) identified the heterogeneous effect of GVC participation on CO_2 intensity among countries at different levels of economic development using data for 43 countries/regions over the period 2000–2014. They employed fixed-effects, two-stage least squares and panel quantile models. The study found a negative impact in the subsample of developed countries and a positive influence for developing countries. However, the latter was insignificant when considering the time trend. Interestingly, the effect of GVC participation was observed solely for low-tech industries, regardless of the subsample analysed. Moreover, the impact differed for the initial CO_2 intensity and technology level. It was more pronounced for developed countries with a high initial CO_2 intensity and developing countries with low CO_2 intensity. Backward GVC participation increased CO_2 intensity, regardless of the group, while forward GVC participation decreased it in developed countries and increased it in developing ones.

Assamoi *et al.* (2020) analyzed the GVC-environment relationship using a sample of 11 Asian countries between 1995 and 2014. They employed fully modified ordinary least squares (OLS) and dynamic OLS models to examine the dynamics between variables. They found that a 1% increase in a country's participation in GVCs lowers CO_2 emissions by 0.28–0.31%. They linked the relationship with improved production and energy efficiency due to technological developments associated with greater participation in GVCs.

Spatial effects related to GVC participation were investigated by Zhu *et al.* (2022) on a sample of 62 countries (regions) from 1995 to 2011 using spatial panel econometric models. The results indicated an inverted U-shaped relationship between participation in GVCs and CO_2 emissions. The study evidenced indirect (spillover) effects of GVC participation (total and backward) in neighbouring regions, which were stronger than the direct effect. These spillover effects varied by industry, with more pronounced effects in manufacturing than in the service sector. The effects were relatively weak for low-tech industries and stronger for hi-tech branches.

Tang *et al.* (2023) focused on the impact of GVC participation on the environmental Kuznets curve turning point using a fixed-effects model. The study used data from the TiVA and Eora databases covering 59 countries between 1995 and 2018, and 104 countries from 1990 to 2018. The study found that an increase in GVC participation lowered the EKC turning point, suggesting that CO_2 emissions begin to decline at lower levels of GDP per capita. Thus, it was beneficial for the environment and was more pronounced for the larger dataset analysed. The in-depth analysis revealed that the environmentally protective effect was induced mainly by GVC forward participation, while the coefficient of backward participation was statistically non-significant.

Wang *et al.* (2022) investigated the relationship between GVC participation, CO_2 emissions and economic growth using a sample of 63 countries and regions from 2005 to 2015. Employing a panel vector autoregressive model, they found that an increase in GVC participation led to a reduction in CO_2 per capita emissions. However, the impact differed by industry and depended on the income level. The decrease in CO_2 emissions was present in high CO_2 industries, irrespective of the value added, and in low CO_2 industries with high value-added. In low value-added industries with low CO_2 emissions, the increase in GVC participation led to a rise in CO_2 emissions in the long run. For high-income countries, the rise in GVC participation showed an initial increase and then a drop in CO_2 emissions, which resulted in a cumulative fall in CO_2 emissions; for low-income economies, increased GVC participation increased carbon dioxide emissions.

Ali and Gniniguè (2022) identified a negative environmental effect of GVC participation using data from 41 African countries between 1990 and 2018. Employing the Driscoll-Kraay fixed effects estimator, they found that CO_2 emissions increased with higher value chain embedding. However, this relationship was moderated by structural transformation, defined as the reallocation of labour from low to high-productivity sectors. The structural transformation itself was found to reduce CO_2 emissions and was positively correlated with GVC participation. They concluded that African countries can foster environmental improvement through GVC integration.

Regarding the mechanism underlying the environmental impact of GVC participation, an important threat for developing countries is that they become mainly involved in carbon intensive and low-value-added actives such as production, processing and assembly as these activities are offshored from developed to developing countries. However, there are also favourable environmental effects for developing countries. The following firm-level studies provide insight into the mechanism of generating environmental benefits within GVCs.

Siewers *et al.* (2024) showed that firms participating in GVCs were more likely to adopt environmentally friendly practices, in particular, to reduce their energy use intensity. They were also more likely to face (and comply with) stricter environmental requirements. The study found that GVC participation improved environmental performance, especially in firms operating in less environmentally demanding domestic markets. Wu *et al.* (2024) evidenced that Chinese firms that engaged in GVCs reduced their sulphur dioxide (SO_2) emissions. This was driven by the scale effect, which reduced SO_2 emissions at high levels of GVC participation but increased them at low levels. More importantly, technology effect enhanced reduction in air pollution associated with GVC integration through increased productivity. Wu *et al.* (2024) interpreted this effect with technology transfer within GVCs, learning effects and the competition effect, i.e., the improvement in technology as a result of exposure to competition in the world market. The environmentally friendly effect of GVC embedding was more pronounced, i.a., in regions with stricter environmental regulations and was mainly observed through a reduction in the use of fossil fuels. Rigo (2021) showed that GVCs served as the foreign technology transfer vehicle in developing countries setting. The study found an increased probability of firms that participate in GVCs adopting foreign licensed technology.

In summary, for emerging and developing countries, GVC participation creates opportunities to learn. However, this ability is determined, i.a., by domestic firms' absorptive capacity (Gentile *et al.*, 2021; Morrison *et al.*, 2008), requiring prior investment (e.g., in R&D) to utilise external knowledge (Cohen & Levinthal, 1989). Therefore, we propose the following hypothesis:

H1: *The impact of GVC participation on air pollution is determined by the country's technological level. Greater GVC participation contributes to a reduction in* CO_2 *emissions as the technology gap shrinks.*

Moreover, we assume that there is a minimum threshold of absorptive capacity for a developing country to benefit from access to technologies through GVC participation (cf. Xu, 2000). GVC-related knowledge (learning within GVCs) is often complemented by learning outside GVCs (De Marchi *et al.*, 2018), in particular within the domestic economy. Based on this premise, we propose:

H2: *Some technological advancement is a necessary condition for a country to reduce CO_2 emissions as a result of technology diffusion through GVCs.*

Our hypotheses suggest that a country's technological advancement can influence the environmental impact of GVC participation. Thus, our research contributes to a very narrow stream in the literature that explores the mutual dependence of GVC integration and a country's technological level in affecting pollution emissions. Below, we provide a detailed review of the most relevant studies.

Wang *et al.* (2021) investigated how the interaction between technological progress and GVC participation affected environmental pollution using data from Brazil, China, India, Mexico, and Russia between 1995 and 2009. Employing a panel threshold model, they found that technological progress can reduce nitrogen oxide and sulphur dioxide emissions when GVC participation exceeded certain thresholds (approximately 0.0995 for nitrogen oxide and 0.2558 for sulphur dioxide in full sample estimation). Below these thresholds, technological progress increased emissions. The results showed some heterogeneity in the impact in particular countries and between manufacturing and service industries.

Yang and Liu (2021) analysed the interplay of GVC involvement and R&D expenditures in affecting carbon dioxide emissions. They utilised panel data from 17 industrial sectors in China from 2005 to 2015 and employed a feasible generalised least squares estimation technique. They found that both GVC involvement and R&D expenditures contributed to a reduction in CO_2 emissions. Notably, the negative impact of GVC participation on CO_2 emissions was more pronounced among high-level R&D industries compared with low-level R&D branches. There was also a stronger negative effect of the GVC position in low-level R&D industries than in high-level R&D ones.

Ye *et al.* (2020) investigated the determinants of carbon intensity in a sample of 39 countries (and manufacturing industries) from 1995 to 2009. They applied system GMM, panel quantile regression estimation techniques and multilevel mediation analysis. They found that an improved GVC position and a rise in GVC backward participation led to a reduction in carbon emission intensity. By contrast, the impact of forward GVC participation was statistically insignificant. Further analysis revealed that reducing the technology gap decreased carbon dioxide emissions directly and indirectly by improving the country's GVC position. The study also highlighted the heterogeneous effect of technological progress (narrowing the technology gap). The effects were more noticeable in industries with greater carbon intensity and among parties not included in Annex I of the Kyoto Protocol.

Methods

To verify our hypotheses, we developed an interaction model. We began with the commonly explored (Jaforullah & King, 2017) quadratic form of the environmental Kuznets curve (EKC) model, which regresses a pollution indicator on income, income squared and energy consumption measure (see, e.g., Acaravci & Ozturk, 2010; Arouri *et al.*, 2012; Ehigiamusoe *et al.*, 2020; Kasman & Duman, 2015; Shahbaz *et al.*, 2013). We extended the model with our first key variable: the GVC participation index. This synthetic measure assesses a country's engagement in GVCs based on trade flows that cross at least two country borders (Fernandes *et al.*, 2022). It is calculated as the sum of foreign value added (import content) in the country's gross export, i.e., GVC backward participation, and the country's share of domestic value added that is further exported to third countries, i.e., GVC forward participation (see, e.g., Kersan-Škabić, 2017, 2019; Koopman *et al.*, 2011; Montalbano *et al.*, 2018; Wang *et al.*, 2021). We then extended the model with a patent-based technology gap indicator, which is our second variable of interest. The indicator serves as a proxy for a country's technological advancement by measuring its distance to the world's technological frontier. Next, we added the interaction term between GVC participation and the technology gap measure. Additionally, we controlled for natural resource rents.

Contrary to common practice, in our specification, we did not use energy consumption because its use as an explanatory variable may result in estimation bias since CO_2 emissions are computed based on energy data, and thus, the series are related to each other (see, e.g., Arminen & Menegaki, 2019; Jaforullah & King, 2017; Lin *et al.*, 2022; Munir *et al.*, 2020). Instead, we use per capita fossil fuel energy consumption and per capita renewable energy consumption. Accordingly, the relevant model is given by the following equation:

$$CO2_{\mathrm{it}} = \alpha_0 + \alpha_1 CO2_{\mathrm{it-1}} + \alpha_2 GDP_{\mathrm{it}} + \alpha_3 GDP_{\mathrm{it}}^2 + \alpha_4 FF_{\mathrm{it}} + \alpha_5 RNEW_{\mathrm{it}} + \\ +\alpha_6 RENT_{\mathrm{it}} + \alpha_7 GVC_{\mathrm{it}} + \alpha_8 TECH\_GAP\_IND_{\mathrm{it}} + \\ +\alpha_9 GVC_{\mathrm{it}} \times TECH\_GAP\_IND_{\mathrm{it}} + \mu_{\mathrm{t}} + \varepsilon_{\mathrm{it}} \quad (1)$$

where *CO2* denotes carbon dioxide emissions (in metric tons per capita), *GDP* is the per capita real gross domestic product (in constant 2010 US$), *FF* is fossil fuel energy consumption per capita, *RNEW* represents renewable energy consumption per capita, *GVC* is the global value chain participation index, and *RENT* denotes natural resource rents (in per cent of GDP). *TECH_GAP_IND* stands for the technology gap indicator measured in per capita terms. We used four different measures of the indicator. The first two are based on the flow of patents in all technologies (*TECH_GAP*) and environment-related technologies (*TECH_GAP_ENV*). The next two measures correspond to these indicators but are calculated with patent stocks (*TECH_GAP_ST*, *TECH_GAP_ENV_ST*). We converted all variables into two-year averages to improve the reliability of the data by reducing cyclical fluctuations and possible measurement errors and transformed them into natural logarithms. μ_t denotes time-fixed effects, while the subscripts *i* and *t* represent country and time, respectively.

Following Ye *et al.* (2020), the technology gap indicators were calculated as follows:

$$TECH\_GAP\_IND_{it} = \frac{TECH\_IND\_US_t - TECH\_IND_{it}}{TECH\_IND\_US_t} \quad (2)$$

In formula (2), *TECH_IND* is the general expression that represents the per capita number of total patents or the per capita number of patents on environment-related technologies, for flows or for stock data. *TECH_IND_US* takes the corresponding values for the US economy, which is treated as a technology leader. The patent stocks were calculated using the perpetual inventory method — PIM (cf. Piva & Vivarelli, 2018).

All the data, except for the GVC participation index and technology gap indicators, are sourced from the World Bank's World Development Indicators (WDI) database, while data on GVCs originate from the World Bank (2020) report. The GVC participation index is based on data from the UNCTAD-Eora database (Lenzen *et al.*, 2012; Lenzen *et al.*, 2013) and computed following the approach by Borin and Mancini (2019). Patent data are from the OECD database (OECD, 2021).

The analysis covers 90 emerging and developing countries[2] over the period 1990–2015. The research period ends in 2015 due to data availability. The descriptive statistics for all variables employed are reported in Table 1.

Considering the econometric method, we used the first-difference GMM estimator by Arellano and Bond (1991)[3] as this estimator is preferred for several reasons. Our dataset covers 90 countries and 13 time periods (after converting the data into two-year averages), providing a relatively large number of individuals (countries) compared to the number of periods. The GMM estimator is particularly suited for wide and short panels (Roodman, 2009b). To avoid estimation bias, the applied technique should account for the model structure and address the endogeneity problem. Our model includes the lagged dependent variable to capture the dynamics in CO_2 emissions. Therefore, the GMM estimator is an appropriate choice as it deals with endogeneity in dynamic panel data models (Roodman, 2009a). Another advantage of this estimator is that it uses internal instrumental variables, which partly solves the problem of finding good external instruments (Roodman, 2009a). However, the technique may introduce bias into the estimates due to instrument proliferation as the time frame increases. Thus, we limited the number of instruments by applying only a reduced number of lags to maintain the instrument count below the number of individuals (countries), as suggested by Roodman (2009b). We also included time-fixed effects in our models to increase the likelihood that the assumption of no correlation across individuals in the idiosyncratic disturbances is satisfied (Roodman, 2009b). To assess the joint validity of the instruments used, we employed Hansen's test of overidentifying restrictions, which supported their validity. Additionally, no second-order autocorrelation of error terms in our models was detected by the Arellano-Bond test.

Results

The estimation results of our model given by Equation (1) are reported in Table 2. The empirical findings support the existence of an inverted U-shaped relationship between CO_2 emissions and economic growth (which is consistent with the EKC hypothesis) since the parameter estimates on per capita GDP and its squared term are both statistically signifi-

[2] The list of countries is given in Appendix.

[3] Stata 16 command xtabond2.

cant (in some regressions at the 10% significance level) and exhibit the expected signs: positive for GDP and negative for its square.

Regarding the energy consumption variables, the positive and statistically significant coefficients on fossil fuel energy consumption indicate that an increase in fossil fuel use leads to higher CO_2 emissions. However, we found no statistically significant impact of renewable energy consumption on environmental quality. The results also indicate a positive and statistically significant relationship (at the 10% level) between natural resource rents and CO_2 emissions. The positive and significant coefficients on the lagged dependent variable imply that the current period's CO_2 emissions are influenced by the previous period's values.

Interpreting the results of multiplicative interaction models differs from linear-additive models. Thus, classic results tables (like Table 2) do not provide enough information for a comprehensive analysis of the conditional relationship (see Brambor *et al.*, 2006). To address this, we additionally calculated the marginal effects of GVC participation on CO_2 emissions as the technology gap changes, expressed as follows[4]:

$$\partial CO2/\,\partial GVC = \alpha_7 + \alpha_9 TECH\_GAP\_IND \tag{3}$$

Figures 1–4 illustrate these marginal effects for the different technology gap indicators. The effects (denoted by a solid line) are regarded as statistically significant only when the two-tailed 95% confidence interval (indicated by error bars) lies above or below the zero axis.

The coefficient on *GVC* provided in Table 2 shows the impact on CO_2 emissions of participating in global value chains when the technology gap indicator (expressed in natural logarithm) equals zero, i.e., the distance to the technological frontier takes the maximum value. The coefficient on the technology gap in Table 2 shows the effect of this indicator on CO_2 emissions when the log-transformed GVC participation index takes the value of zero. This scenario is not observed in our sample, as it would imply that the share of foreign value added and domestic value added that is re-exported to third countries accounts for 100% of a country's gross exports. We are not directly interested in analysing such special cases; thus, we focus on interpreting the marginal effects presented in Figures 1–4.

All marginal effects of GVC participation on CO_2 emissions as the technology gap changes, as presented in Figures 1–4, show a similar pattern.

[4] We have omitted time and cross-section subscripts.

The solid lines, which illustrate these effects, are rising and lie almost entirely below the zero axis, indicating that the effects take negative values and are diminishing. In other words, greater GVC engagement contributes to emissions reduction; however, this environmentally positive effect declines as the technology gap grows. This relationship is statistically significant only up to a threshold value of the technology gap indicator, i.e., only more technologically advanced countries (with smaller technology gaps) enjoy a decline in CO_2 emissions as GVC participation increases.

The emissions reduction effect of GVC participation is higher for the technology gap indicators based on patent activity in environment-related technologies (compare Figure 2 vs 1, and Figure 4 vs 3). It is also higher when the distance to the world's technological frontier is calculated using patent stocks rather than flows (compare Figure 3 vs 1, and Figure 4 vs 2), i.e., when the indicator reflects the cumulative nature of knowledge.

The results imply that the impact of GVC participation on CO_2 emissions is determined by the country's technological level. In economies with a smaller technology gap, greater GVC participation causes a decline in CO_2 emissions. However, this influence diminishes as the technology gap grows. The effect becomes statistically insignificant in economies with a higher technology gap. Thus, our findings strongly support our first hypothesis (H1), which posits that participation in global value chains has a conditional influence on CO_2 emissions. The findings also confirm our second hypothesis (H2), indicating that integration with global value chains decreases a country's CO_2 emissions only when a certain level of technological development is exceeded. Emerging and developing economies with a relatively large technology gap may not experience the improved environmental quality that potentially results from clean technology diffusion due to insufficient absorptive capacity.

As a robustness check of the results, we re-estimated the model with additional variables and controlled for industrial structure and personal remittances. To assess the impact of industrial structure, we used two variables from the WDI database: industry value added as a percentage of GDP and services value added as a percentage of GDP. We first recalculated the model only with industry value added and then with both variables. We also checked the impact of personal remittances received per capita in constant 2010 US$ (calculated with the WDI data). However, expanding the model with additional variables did not change the general conclusions on the modifying role of a country's technological level in the GVC participation-CO_2 emissions relationship. Moreover, their impact on CO_2 emissions was statistically insignificant. Thus, to converse space, we have omitted the estimation results from the article.

Discussion

This study aimed to broaden understanding of the impact of GVC involvement on CO_2 emissions. Unlike other studies that analysed the direct/unconditional effect (Assamoi *et al.*, 2020; Chen *et al.*, 2022; Espinosa-Gracia *et al.*, 2023; Jin *et al.*, 2022; Ma *et al.*, 2022), we revisited this relationship in the context of a country's technological level and verified the impact of GVC participation on CO_2 emissions conditional on a country's level of technological advancement. To the best of our knowledge, only a few studies investigated how GVCs and a country's technological level affect air pollution. Thus, the joint examination of these three variables forms the main contribution of this paper.

The relationship between GVCs, technological progress and environmental pollution was addressed in previous research by Wang *et al.* (2021), Yang and Liu (2021), and Ye *et al.* (2020). However, our analysis differs from these studies in many aspects. Most importantly, Wang *et al.* (2021) and Ye *et al.* (2020) focused on the impact of technological advancement on air pollution rather than the influence of GVCs, as explored in our study, which hinders the direct comparison of the results. Wang *et al.* (2021) examined the effect of technological progress on environmental pollution emissions (nitrogen oxide and sulphur dioxide), taking GVC participation as the threshold variable. Ye *et al*. (2020) investigated the impact of the technology gap on carbon intensity under the mediating role of GVC positioning. By contrast, our analysis explores the moderating role of the technology gap in the relationship between GVC participation and CO_2 emissions. Moreover, the studies differ in methodologies, datasets and dependent variables. Yang and Liu (2021) investigated the interaction effects of GVC involvement and R&D expenditures with CO_2 emissions. They found complementarity between GVC participation and R&D. GVC participation had a stronger negative relationship with carbon emissions in high-level R&D than in low-level R&D, which aligns with our findings. However, their study was entirely dedicated to one country, China, limiting the generalisability of their findings to other countries.

Our results indicate that GVC participation alone may not help mitigate CO_2 emissions in emerging and developing countries, as the impact of GVC participation on CO_2 emissions depends on the country's technological level. Greater GVC participation leads to lower CO_2 emissions as the technology gap shrinks. This finding supports our first hypothesis (H1), confirming the conditional role of a country's technological gap in the GVC participation-CO_2 emissions nexus.

The results also support our second hypothesis (H2), indicating that a certain technological level is necessary for a country to absorb advanced and clean technologies from developed countries. Thus, reaping environmental benefits from GVC participation is closely related to a country's technological advancement, which determines the country's ability to acquire and exploit external knowledge. Consequently, our analysis gives a new perspective on how global value chain involvement impacts CO_2 emissions.

Additionally, our findings show that natural resource exploitation exacerbates CO_2 emissions in emerging and developing economies. This outcome aligns with the empirical evidence from Cai *et al.* (2023) and Khattak *et al.* (2024) for the BRICS countries, Gyamfi *et al.* (2022) for G7 economies, Ulucak *et al.* (2020) for OECD countries, Adedoyin *et al*. (2020) for sub-Saharan African countries (in the long run), and Hassan *et al.* (2021) for Pakistan (except for the short run). However, our findings contradict those of Balsalobre-Lorente *et al.* (2018) for EU-5 countries, which evidenced that natural resource abundance improves environmental quality. The analysis by Khattak *et al.* (2024) provided mixed results at the country level, as natural resource rents facilitated CO_2 reduction only in certain countries, i.e., Brazil and Russia.

We have also confirmed the existence of the environmental Kuznets curve, which is in line with the findings from numerous prior studies (Ali & Gniniguè, 2022; Amin *et al.*, 2020; Assamoi *et al.*, 2020; Gyamfi *et al.*, 2022; Haldar & Sethi, 2021; Li & Haneklaus, 2021; Wawrzyniak & Doryń, 2020).

Regarding energy consumption variables, our results show that fossil fuel energy consumption increased CO_2 emissions, affirming the findings from Gyamfi *et al.* (2022) for G7 economies, Li and Haneklaus (2021) for China in the long term, and Wawrzyniak and Doryń (2020) for emerging and developing countries. The impact of renewable energy consumption on CO_2 emissions was statistically insignificant in our analysis. While this aligns with Wawrzyniak and Doryń (2020) for emerging and developing countries, it contradicts Ali and Gniniguè (2022) for African countries, Amin *et al.* (2020) for European countries, Gyamfi *et al.* (2022) for G7 economies, and Haldar and Sethi (2021) for developing countries, all of whom reported a negative impact.

Conclusions

This study aimed to deepen understanding of how involvement in GVCs affects CO_2 emissions, considering the moderating effect of a country's technological level in emerging and developing nations. It explored the relationship between GVC participation and CO_2 emissions through the lens of technological advancement, offering new insights into this relationship and the underlying mechanism.

The findings have confirmed the conditional influence of a country's participation in GVCs on CO_2 emissions. Specifically, greater participation reduces CO_2 emissions in more technologically advanced economies and the environmentally positive effect declines as the distance to the world's technological frontier grows. Beyond a certain threshold in the technology gap, the impact becomes statistically insignificant. In other words, in emerging and developing countries, participation in GVCs can help reduce CO_2 emissions, but only when the country has an initial level of technological advancement. Economies that are further from the world's technological frontier may not be able to experience improved environmental quality as a result of technology diffusion through GVCs due to their insufficient absorptive capacity. Additionally, a decline in CO_2 emissions with higher GVC involvement was more pronounced for indicators based on environment-related technologies and when the cumulative nature of knowledge (patent stocks) was considered.

Our findings introduce a new perspective on environmental consequences arising from GVC participation in emerging and developing countries. They show that an initial level of technology in emerging and developing countries is essential for transferring clean technology via GVCs from advanced economies. Consequently, mere participation in GVCs will not solve the problem of environmental pollution. Countries must progress technologically if they are to reap the environmental benefits associated with GVC participation. This finding is of crucial importance given that developing countries are experiencing the highest growth rates in emissions. Based on these insights, we propose the following policy recommendations:

1. Emerging and developing countries should actively participate in GVCs as this can enable them to enjoy the environmental benefits related to the transfer of clean technologies from advanced countries. For developing countries, GVCs may serve as a bridge to environmental progress. However, they should be cautious and selectively participate in GVCs to avoid involvement in environmentally harmful activities. Governments should promote policies fostering participation in GVCs while taking steps to prevent the country from becoming a "pollution haven".
2. Our study indicates that adopting new technologies through GVCs is not an automatic process; it depends on a country's absorptive capacity. Thus, emerging and developing economies should invest in technological development and skill-building to improve their ability to acquire and exploit external knowledge. In this context, national policies play a crucial role. However, financial constraints may hinder these countries from taking the necessary steps and achieving their goal, necessitating international support.
3. Reducing CO_2 emissions in emerging and developing countries requires international cooperation. Specifically, developed countries should facilitate rather than restrict the transfer of expertise, environmentally friendly technologies and innovations to developing economies.

In summary, reducing carbon emissions in emerging and developing countries requires multidimensional actions and international efforts.

Additionally, our study contributes theoretically by expanding knowledge on how technological advancement shapes the relationship between GVC participation and CO_2 emissions, exposing the underlying mechanism. Though our study sheds new light on the moderating role of the technology gap in the relationship between GVC participation and CO_2 emissions, it suffers from several limitations.

The first limitation concerns the dependent variable used. The hypotheses were only tested for CO_2 emissions; thus, generalising the findings to other pollutants must be done with caution. Future research should broaden the approach to other air pollutants. The second limitation refers to the technology gap indicator used. We used a patent-based indicator, which has some drawbacks. While this indicator reflects technological advancement, it does not account for the practical application of that technology (Du *et al.*, 2019). Moreover, the research ends before the outbreak of the

COVID-19 pandemic. Thus, it does not consider the collapse of GVC trade as a consequence of the COVID-19 disruption.

Despite these limitations, we hope that this paper opens avenues for more in-depth research on the role of technological advancement in shaping the influence of GVC participation on air pollution, as our analysis provides only preliminary conclusions.

References

Acaravci, A., & Ozturk, I. F. (2010). On the relationship between energy consumption, CO_2 emissions and economic growth in Europe. *Energy*, *35*(12), 5412–5420. https://doi.org/10.1016/j.energy.2010.07.009.

Adedoyin, F. F., Alola, A. A., & Bekun, F. V. (2020). The nexus of environmental sustainability and agro-economic performance of Sub-Saharan African countries. *Heliyon*, *6*(9), e04878. https://doi.org/10.1016/j.heliyon.2020.e04878.

Agostino, M., Giunta, A., Ruberto, S., & Scalera, D. (2023). Global value chains and energy-related sustainable practices. Evidence from Enterprise Survey data. *Energy Economics*, *127*, 107068. https://doi.org/10.1016/j.eneco.2023.107068.

Ali, E., & Gniniguè, M. (2022). Global value chains participation and structural transformation in Africa: Are we advocating environmental protection? *Journal of Cleaner Production*, *366*, 132914. https://doi.org/10.1016/j.jclepro.2022.132914.

Ali, E., Gniniguè, M., & Awade, N. E. (2023). Sectoral value chains and environmental pollution in Africa: Can development policies target digitalization and structural transformation to enhance environmental governance? *Journal of Environmental Economics and Policy*, *12*(2), 229–247. https://doi.org/10.1080/21606544.2022.2110163.

Amin, A., Altinoz, B., & Dogan, E. (2020). Analyzing the determinants of carbon emissions from transportation in European countries: The role of renewable energy and urbanization. *Clean Technologies and Environmental Policy*, *22*, 1725–1734. https://doi.org/10.1007/s10098-020-01910-2.

Ansari, M. A., & Khan, N. A. (2021). Decomposing the trade-environment nexus for high income, upper and lower middle income countries: What do the composition, scale, and technique effect indicate? *Ecological Indicators*, *121*, 107122. https://doi.org/10.1016/j.ecolind.2020.107122.

Antràs, P. (2020). Conceptual aspects of global value chains. *World Bank Economic Review*, *34*(3), 551–574. https://doi.org/10.1093/wber/lhaa006.

Arellano, M., & Bond, S. (1991). Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *Review of Economic Studies*, *58*(2), 277–297. https://doi.org/10.2307/2297968.

Arminen, H., & Menegaki, A. N. (2019). Corruption, climate and the energy-environment growth nexus. *Energy Economics*, *80*, 621–634. https://doi.org/10.1016/j.eneco.2019.02.009.

Arouri, M. H., Youssef, B. A., M'henni, H., & Rault, C. (2012). Energy consumption, economic growth and CO_2 emissions in Middle East and North African countries. *Energy Policy*, *45*, 342–349. https://doi.org/10.1016/j.enpol.2012.02.042.

Assamoi, G. R., Wang, S., Liu, Y., Gnangoin, T. B. Y., Kassi, D. F., & Edjoukou, A. J. R. (2020). Dynamics between participation in global value chains and carbon dioxide emissions: Empirical evidence for selected Asian countries. *Environmental Science and Pollution Research*, *27*(14), 16496–16506. https://doi.org/10.1007/s11356-020-08166-9.

Avom, D., Nkengfack, H., Fotio, H. K., & Totouom, A. (2020). ICT and environmental quality in Sub-Saharan Africa: Effects and transmission channels. *Technological Forecasting and Social Change*, *155*, 120028. https://doi.org/10.1016/j.techfore.2020.120028.

Azam, M., Rehman, Z. U., & Ibrahim, Y. (2022). Causal nexus in industrialization, urbanization, trade openness, and carbon emissions: Empirical evidence from OPEC economies. *Environment, Development and Sustainability*, *24*, 13990–14010. https://doi.org/10.1007/s10668-021-02019-2.

Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., & Farhani, S. (2018). How economic growth, renewable electricity and natural resources contribute to CO_2 emissions? *Energy Policy*, *113*, 356–367. https://doi.org/10.1016/j.enpol.2017.10.050.

Borin, A., & Mancini, M. (2019). Measuring what matters in global value chains and value-added trade. *Policy Research Working Paper*, *8804*. https://doi.org/10.1596/1813-9450-8804.

Borowiec, J., & Papież, M. (2024). Convergence of CO_2 emissions in countries at different stages of development. Do globalisation and environmental policies matter? *Energy Policy*, *184*, 113866. https://doi.org/10.1016/j.enpol.2023.113866.

Brambor, T., Clark, W. R., & Golder, M. (2006). Understanding interaction models: Improving empirical analyses. *Political Analysis*, *14*(1), 63–82. https://doi.org/10.1093/pan/mpi014.

Burki, U., & Tahir, M. (2022). Determinants of environmental degradation: Evidenced-based insights from ASEAN economies. *Journal of Environmental Management*, *306*, 114506. https://doi.org/10.1016/j.jenvman.2022.114506.

Cai, X., Li, K., Wang, W., Lu, Y., & Wang, R. (2023). The role of resource rent in shaping CO_2 emissions in BRICS countries: A panel data approach. *Resources Policy*, *85*, 103857. https://doi.org/10.1016/j.resourpol.2023.103857.

Chen, H., Zhang, C., & Yin, K. (2022). The impact of global value chain embedding on carbon emissions embodied in China's exports. *Frontiers in Environmental Science*, *10*, 950869. https://doi.org/10.3389/fenvs.2022.950869.

Chen, S., Akimoto, K., Sun, Y., Kagatsume, M., & Wang, N. (2021). The sustainability of regional decarbonization through the global value chain analytical framework: A case study of Germany. *Journal of Cleaner Production*, *317*, 128335. https://doi.org/10.1016/j.jclepro.2021.128335.

Chen, Y., & Lee, C. C. (2020). Does technological innovation reduce CO_2 emissions? Cross-country evidence. *Journal of Cleaner Production*, *263*, 121550. https://doi.org/10.1016/j.jclepro.2020.121550.

Cohen, W. M., & Levinthal, D. A. (1989). Innovation and learning: The two faces of R&D. *Economic Journal*, *99*(397), 569–596. https://doi.org/10.2307/2233763.

Dauda, L., Long, X., Mensah, C. N., Salman, M., Boamah, K. B., Ampon-Wireko, S., & Dogbe, C. S. K. (2021). Innovation, trade openness and CO_2 emissions in selected countries in Africa. *Journal of Cleaner Production*, *281*, 125143. https://doi.org/10.1016/j.jclepro.2020.125143.

De Marchi, V., Giuliani, E., & Rabellotti, R. (2018). Do global value chains offer developing countries learning and innovation opportunities? *European Journal of Development Research*, *30*, 389–407. https://doi.org/10.1057/s41287-017-0126-z.

Dietzenbacher, E., & Yan, B. (2024). Explaining the direction of emissions embodied in trade from hypotheses based on country rankings. *Energy Economics*, *129*, 107188. https://doi.org/10.1016/j.eneco.2023.107188.

Dong, K., Hochman, G., & Timilsina, G. R. (2020). Do drivers of CO_2 emission growth alter overtime and by the stage of economic development? *Energy Policy*, *140*, 111420. https://doi.org/10.1016/j.enpol.2020.111420.

Du, K., Li, P., & Yan, Z. (2019). Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data. *Technological Forecasting and Social Change*, *146*, 297–303. https://doi.org/10.1016/j.techfore.2019.06.010.

Ehigiamusoe, K. U., Lean, H. H., & Smyth, R. (2020). The moderating role of energy consumption in the carbon emissions-income nexus in middle-income countries. *Applied Energy*, *261*, 114215. https://doi.org/10.1016/j.apenergy.2019.114215.

Espinosa-Gracia, A., Almazán-Gómez, M. Á., & Jiménez, S. (2023). CO_2 emissions and global value chains indicators: New evidence for 1995–2018. *Journal of Environmental Management*, *343*, 118239. https://doi.org/10.1016/j.jenvman.2023.118239.

Fagerberg, J., Lundvall, B. Å., & Srholec, M. (2018). Global value chains, national innovation systems and economic development. *European Journal of Development Research*, *30*(3), 533–556. https://doi.org/10.1057/s41287-018-0147-2.

Farooq, U., Tabash, M. I., Anagreh, S., Al-Rdaydeh, M., & Habib, S. (2023). Economic growth, foreign investment, tourism, and electricity production as determinants of environmental quality: Empirical evidence from GCC region. *Environmental Science and Pollution Research*, *30*(16), 45768–45780. https://doi.org/10.1007/s11356-023-25545-0.

Fernandes, A., Kee, H. L., & Winkler, D. (2022). Determinants of global value chain participation: cross-country evidence. *World Bank Economic Review*, *36*(2), 329–360. https://doi.org/10.1093/wber/lhab017.

Gentile, E., Xing, Y., Rubínová, S., & Huang, S. (2021). Productivity growth, innovation, and upgrading along global value chains. In Y. Xing, E. Gentile & D. Dollar (Eds.). *Beyond production. GVC development report 2021* (pp. 72–104). World Trade Organization.

Grossman, G. M., & Krueger, A. B. (1991). Environmental impacts of a North American free trade agreement. *NBER Working Paper Series*, *3194*.

Gyamfi, B. A., Onifade, S. T., Nwani, C., & Bekun, F. V. (2022). Accounting for the combined impacts of natural resources rent, income level, and energy consumption on environmental quality of G7 economies: A panel quantile regression approach. *Environmental Science and Pollution Research*, *29*(2), 2806–2818. https://doi.org/10.1007/s11356-021-15756-8.

Habiba, U. M. M. E., Xinbang, C., & Anwar, A. (2022). Do green technology innovations, financial development, and renewable energy use help to curb carbon emissions? *Renewable Energy*, *193*, 1082–1093. https://doi.org/10.1016/j.renene.2022.05.084.

Haini, H. (2021). Examining the impact of ICT, human capital and carbon emissions: Evidence from the ASEAN economies. *International Economics*, *166*, 116–125. https://doi.org/10.1016/j.inteco.2021.03.003.

Haldar, A., & Sethi, N. (2021). Effect of institutional quality and renewable energy consumption on CO_2 emissions − an empirical investigation for developing countries. *Environmental Science and Pollution Research*, *28*(12), 15485–15503. https://doi.org/10.1007/s11356-020-11532-2.

Hassan, S. T., Xia, E., & Lee, C.-C. (2021). Mitigation pathways impact of climate change and improving sustainable development: The roles of natural resources, income, and CO_2 emission. *Energy & Environment*, *32*(2), 338–363. https://doi.org/10.1177/0958305X20932550.

Jaforullah, M., & King, A. (2017). The econometric consequences of an energy consumption variable in a model of CO_2 emissions. *Energy Economics*, *63*, 84–91. https://doi.org/10.1016/j.eneco.2017.01.025.

Jin, Z.-D., Duan, H.-B., Wang, J.-C., Yang, M., Guo, Y.-H., & Cui, X.-D. (2022). Heterogeneous impacts of GVCs participation on CO_2 intensity: Evidence from developed and developing countries/regions. *Advances in Climate Change Research, 13*(2), 187–195, https://doi.org/10.1016/j.accre.2022.01.002.

Kasman, A., & Duman, Y. S. (2015). CO_2 emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: a panel data analysis. *Economic Modelling*, *44*, 97–103. https://doi.org/10.1016/j.econmod.2014.10.022.

Kersan-Škabić, I. (2017). Assessment of EU member states' positions in global value chains. *Eastern Journal of European Studies*, *8*(2), 5–24.

Kersan-Škabić, I. (2019). The drivers of global value chain (GVC) participation in EU member states. *Economic Research-Ekonomska Istraživanja*, *32*(1), 1204–1218. https://doi.org/10.1080/1331677X.2019.1629978.

Khattak, S. I., Khan, A., & Hussain, K. (2024). Green technology innovations, natural gas and resource extraction strategies in BRICS: Modeling impacts on CO_2 emission intensity. *Sustainable Futures*, *7*, 100227. https://doi.org/10.1016/j.sftr.2024.100227.

Koopman, R., Powers, W., Wang, Z., & Wei, S.-J. (2011). Give credit to where credit is due: Tracing value added in global production chains. *NBER Working Paper Series, 16426*. https://doi.org/10.3386/w16426.

Lenzen, M., Kanemoto, K., Moran, D., & Geschke, A. (2012). Mapping the structure of the world economy. *Environmental Science & Technology*, *46*(15), 8374–8381. https://doi.org/10.1021/es300171x.

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: A global multi-regional input-output database at high country and sector resolution. *Economic Systems Research*, *25*(1), 20–49. https://doi.org/10.1080/09535314.2013.769938.

Li, B., & Haneklaus, N. (2021). The role of renewable energy, fossil fuel consumption, urbanization and economic growth on CO_2 emissions in China. *Energy Reports*, *7*, 783–791. https://doi.org/10.1016/j.egyr.2021.09.194.

Li, B., & Haneklaus, N. (2022). Reducing CO_2 emissions in G7 countries: The role of clean energy consumption, trade openness and urbanization. *Energy Reports*, *8*, 704–713. https://doi.org/10.1016/j.egyr.2022.01.238.

Lin, H., Wang, X., Bao, G., & Xiao, H. (2022). Heterogeneous spatial effects of FDI on CO_2 emissions in China. *Earth's Future, 10*(1), e2021EF002331. https://doi.org/10.1029/2021EF002331.

Ma, X., Liu, X., Pan, X., & Liao, X. (2022). Global value chain participation impacts carbon emissions–Take the electro-optical equipment industry as an example. *Frontiers in Environmental Science*, *10*, 943801. https://doi.org/10.3389/fenvs.2022.943801.

Meng, B., Ye, M., & Wei, S. J. (2020). Measuring smile curves in global value chains. *Oxford Bulletin of Economics and Statistics*, *82*(5), 988–1016. https://doi.org/10.1111/obes.12364.

Mert, M., & Caglar, A. E. (2020). Testing pollution haven and pollution halo hypotheses for Turkey: A new perspective. *Environmental Science and Pollution Research*, *27*, 32933–32943. https://doi.org/10.1007/s11356-020-09469-7.

Montalbano, P., Nenci, S., & Pietrobelli, C. (2018). Opening and linking up: Firms, GVCs, and productivity in Latin America. *Small Business Economics*, *50*(4), 917–935. https://doi.org/10.1007/s11187-017-9902-6.

Morrison, A., Pietrobelli, C., & Rabellotti, R. (2008). Global value chains and technological capabilities: a framework to study learning and innovation in developing countries. *Oxford Development Studies*, *36*(1), 39–58. https://doi.org/10.1080/13600810701848144.

Muhammad, S., & Long, X. (2021). Rule of law and CO_2 emissions: A comparative analysis across 65 Belt and Road initiative (BRI) countries. *Journal of Cleaner Production*, *279*, 123539. https://doi.org/10.1016/j.jclepro.2020.123539.

Munir, Q., Lean, H.H., & Smyth R. (2020). CO_2 emissions, energy consumption and economic growth in the ASEAN-5 countries: A cross-sectional dependence approach. *Energy Economics*, *85*, 104571. https://doi.org/10.1016/j.eneco.2019.104571.

Nguyen, D. K., Huynh, T. L. D., & Nasir, M. A. (2021). Carbon emissions determinants and forecasting: Evidence from G6 countries. *Journal of Environmental Management*, *285*, 111988. https://doi.org/10.1016/j.jenvman.2021.111988.

OECD (2021). Patents in environment-related technologies: Technology development by inventor country. OECD Environment Statistics [database]. https://doi.org/10.1787/data-00760-en.

Ofori, E. K., Onifade, S. T., Ali, E. B., Alola, A. A., & Zhang, J. (2023). Achieving carbon neutrality in post COP26 in BRICS, MINT, and G7 economies: The role of financial development and governance indicators. *Journal of Cleaner Production*, *387*, 135853. https://doi.org/10.1016/j.jclepro.2023.135853.

Patel, N., & Mehta, D. (2023). The asymmetry effect of industrialization, financial development and globalization on CO_2 emissions in India. *International Journal of Thermofluids*, *20*, 100397. https://doi.org/10.1016/j.ijft.2023.100397.

Piva, M., & Vivarelli, M. (2018). Technological change and employment: Is Europe ready for the challenge? *Eurasian Business Review*, *8*(1), 13–32. https://doi.org/10.1007/s40821-017-0100-x.

Qian, Z., Zhao, Y., Shi, Q., Zheng, L., Wang, S., & Zhu, J. (2022). Global value chains participation and CO_2 emissions in RCEP countries. *Journal of Cleaner Production*, *332*, 130070. https://doi.org/10.1016/j.jclepro.2021.130070.

Rigo, D. (2021). Global value chains and technology transfer: New evidence from developing countries. *Review of World Economics*, *157*(2), 271–294. https://doi.org/10.1007/s10290-020-00398-8.

Roodman, D. (2009a). A note on the theme of too many instruments. *Oxford Bulletin of Economics and Statistics*, *71*(1), 135–158. https://doi.org/10.1111/j.1468-0084.2008.00542.x.

Roodman, D. (2009b). How to do xtabond2: An introduction to difference and system GMM in Stata. *Stata Journal: Promoting Communications on Statistics and Stata, 9*(1), 86–136. https://doi.org/10.1177/1536867X0900900106.

Shahbaz, M., Mutascu, M., & Azim, P. (2013). Environmental Kuznets curve in Romania and the role of energy consumption. *Renewable and Sustainable Energy Reviews*, *18*, 165–173. https://doi.org/10.1016/j.rser.2012.10.012.

Siewers, S., Martínez-Zarzoso, I., & Baghdadi, L. (2024). Global value chains and firms' environmental performance. *World Development*, *173*, 106395. https://doi.org/10.1016/j.worlddev.2023.106395.

Singhania, M., & Saini, N. (2021). Demystifying pollution haven hypothesis: Role of FDI. *Journal of Business Research*, *123*, 516–528. https://doi.org/10.1016/j.jbusres.2020.10.007.

Tang, Y., Qiao, X., & Zhu, Y. (2023). Global Value Chains and the environmental Kuznets Curve: Promotion or hindrance? *Applied Economics Letters*, *30*(14), 1913–1917. https://doi.org/10.1080/13504851.2022.2083564.

Twerefou, D. K., Akpalu, W., & Mensah, A. C. E. (2019). Trade-induced environmental quality: The role of factor endowment and environmental regulation in Africa. *Climate and Development*, *11*(9), 786–798. https://doi.org/10.1080/17565529.2018.1562868.

Uche, E., Das, N., Bera, P., & Cifuentes-Faura, J. (2023). Understanding the imperativeness of environmental-related technological innovations in the FDI–Environmental performance nexus. *Renewable Energy*, *206*, 285–294. https://doi.org/10.1016/j.renene.2023.02.060.

Ulucak, R., Danish, & Ozcan, B. (2020). Relationship between energy consumption and environmental sustainability in OECD countries: The role of natural resources rents. *Resources Policy*, *69*, 101803. https://doi.org/10.1016/j.resourpol.2020.101803.

Umar, M., Raza, M. Y., & Xu, Y. (2023). Determinants of CO_2 emissions and economic progress: A case from a developing economy. *Heliyon*, *9*(1), e12303. https://doi.org./10.1016/j.heliyon.2022.e12303.

Wang, J., Rickman, D. S., & Yu, Y. (2022). Dynamics between global value chain participation, CO_2 emissions, and economic growth: Evidence from a panel vector autoregression model. *Energy Economics*, *109*(2022), 105965. https://doi.org/10.1016/j.eneco.2022.105965.

Wang, J., Wan, G., & Wang, C. (2019). Participation in GVCs and CO_2 emissions. *Energy Economics*, *84*, 104561. https://doi.org/10.1016/j.eneco.2019.104561.

Wang, Q., Wang, L., & Li, R. (2023). Trade protectionism jeopardizes carbon neutrality–decoupling and breakpoints roles of trade openness. *Sustainable Production and Consumption*, *35*, 201–215. https://doi.org/10.1016/j.spc.2022.08.034.

Wang, S., He, Y., & Song, M. (2021). Global value chains, technological progress, and the environmental pollution: Inequality towards developing countries. *Journal of Environmental Management*, *277*, 110999. https://doi.org/10.1016/j.jenvman.2020.110999.

Wawrzyniak, D., & Doryń, W. (2020). Does the quality of institutions modify the economic growth-carbon dioxide emissions nexus? Evidence from a group of emerging and developing countries. *Economic Research-Ekonomska Istraživanja*, *33*(1), 124–144. https://doi.org/10.1080/1331677X.2019.1708770.

World Bank (2020). *World Development Report 2020: Trading for development in the age of global value chains*, Washington, D.C., [database]. Retrieved from http://pubdocs.worldbank.org/en/834031570559525797/Chapter-1.zip (23.02.2020).

Wu, R., Wang, J., Wang, S., & Feng, K. (2021). The drivers of declining CO_2 emissions trends in developed nations using an extended STIRPAT model: A historical and prospective analysis. *Renewable and Sustainable Energy Reviews*, *149*, 111328. https://doi.org/10.1016/j.rser.2021.111328.

Wu, S., Wei, T., Qu, Y., Xue, R., Wang, H., & Shan, Y. (2024). How does global value chain embeddedness affect environmental pollution? Evidence from Chinese enterprises. *Journal of Cleaner Production*, *434*, 140232. https://doi.org/10.1016/j.jclepro.2023.140232.

Xin, D., Ahmad, M., Lei, H., & Khattak, S.I. (2021). Do innovation in environmental-related technologies asymmetrically affect carbon dioxide emissions in the United States? *Technology in Society*, 67, 101761. https://doi.org/10.1016/j.techsoc.2021.101761.

Xu, B. (2000). Multinational enterprises, technology diffusion, and host country productivity growth. *Journal of Development Economics*, *62*(2), 477–493. https://doi.org/10.1016/S0304-3878(00)00093-6.

Yang, N., & Liu, Q. (2021). The interaction effects of GVC involvement and domestic R&D on carbon emissions: evidence from China's industrial sectors. *Technology Analysis & Strategic Management*, *34*(6), 687–702. https://doi.org./10.1080/09537325.2021.1916456.

Yasin, I., Ahmad, N., & Chaudhary, M. A. (2021). The impact of financial development, political institutions, and urbanization on environmental degradation: Evidence from 59 less-developed economies. *Environment, Development and Sustainability*, *23*, 6698–6721. https://doi.org/10.1007/s10668-020-00885-w.

Ye, C., Ye, Q., Shi, X., & Sun, Y. (2020). Technology gap, global value chain and carbon intensity: Evidence from global manufacturing industries. *Energy Policy*, *137*, 111094. https://doi.org./10.1016/j.enpol.2019.111094.

Zhu, S., Tang, Y., Qiao, X., You, W., & Peng, C. (2022). Spatial effects of participation in global value chains on CO_2 emissions: A global spillover perspective. *Emerging Markets Finance and Trade*, *58*(3), 776–789. https://doi.org./10.1080/1540496X.2021.1911801.

Zmami, M., & Ben-Salha, O. (2020). An empirical analysis of the determinants of CO_2 emissions in GCC countries. *International Journal of Sustainable Development & World Ecology*, *27*(5), 469–480. https://doi.org/10.1080/13504509.2020.1715508.

Compliance with ethical standards

This article does not contain any studies with human participants or animals performed by the authors. Extracting and inspecting publicly accessible files (scholarly sources) as evidence, before the research began no institutional ethics approval was required.

Data availability statement

All data generated or analyzed are included in the published article. The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation. The raw anonymized data can be provided by emailing the primary author.

Author contributions

All listed authors have made a substantial, direct and intellectual contribution to the work, and approved it for publication. The authors take full responsibility for the accuracy and the integrity of the source analysis.

Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Annex

Table 1. Summary statistics

Variable	Mean	Std. Dev.	Min	Max
CO2	0.443	1.313	-3.146	3.407
GDP	7.985	1.056	5.199	11.066
FF	6.196	1.387	2.487	9.611
RNEW	5.064	1.254	-0.880	7.808
GVC	-0.985	0.267	-1.639	-0.143
RENT	1.178	1.660	-6.566	4.168
TECH_GAP	-0.016	0.042	-0.394	0
TECH_GAP_ENV	-0.020	0.048	-0.434	0
TECH_GAP_ST	-0.017	0.045	-0.396	0
TECH_GAP_ENV_ST	-0.022	0.053	-0.538	0

Notes: The figures refer to variables converted into two-year averages and log-transformed.
For the technology gap indicators, zero denotes the highest possible distance from the technological frontier, while more negative values reflect a shorter distance to the frontier.

Table 2. Estimation results of the interaction model with the technology gap indicator as the modifying variable

Variables	(1)	(2)	(3)	(4)
$CO2_{t-1}$	0.326***	0.313***	0.329***	0.318***
	(0.109)	(0.106)	(0.110)	(0.108)
GDP	0.931**	0.942**	0.998**	1.078**
	(0.464)	(0.466)	(0.466)	(0.494)
GDP^2	-0.048*	-0.049*	-0.054*	-0.059**
	(0.028)	(0.028)	(0.028)	(0.029)
FF	0.519***	0.524***	0.525***	0.514***
	(0.155)	(0.152)	(0.150)	(0.153)
RNEW	0.018	0.007	0.027	0.040
	(0.042)	(0.053)	(0.045)	(0.060)
RENT	0.046*	0.048*	0.046*	0.048*
	(0.024)	(0.025)	(0.024)	(0.025)
GVC	0.047	0.060	0.069	0.087
	(0.128)	(0.137)	(0.126)	(0.135)
TECH_GAP	2.952**			
	(1.299)			
GVC × TECH_GAP	3.556**			
	(1.690)			
TECH_GAP_ENV		2.825**		
		(1.368)		

Table 2. Continued

Variables	(1)	(2)	(3)	(4)
GVC × TECH_GAP_ENV		3.658**		
		(1.602)		
TECH_GAP_ST			3.264**	
			(1.495)	
GVC × TECH_GAP_ST			3.890**	
			(1.921)	
TECH_GAP_ENV_ST				3.313*
				(1.696)
GVC × TECH_GAP_ENV_ST				4.333**
				(2.107)
Time dummies	Yes	Yes	Yes	Yes
N	940	940	940	940
Number of ids	90	90	90	90
AR(1) (p-value)	0.092	0.142	0.067	0.085
AR(2) (p-value)	0.856	0.999	0.742	0.758
Hansen's (p-value)	0.587	0.779	0.750	0.716
Number of instruments	87	87	87	87

Notes: Heteroscedasticity and autocorrelation robust standard errors in parentheses.
Asterisks indicate significance at levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.
Instruments used: *$CO2_{t-1}$, GDP, FF, RNEW, RENT, GVC, TECH_GAP, TECH_GAP_ENV, TECH_GAP_ST, TECH_GAP_ENV_ST* – lags 2 to 2.
Year dummies are considered strictly exogenous.

Figure 1. The average marginal effect of GVC participation on CO_2 emissions as the technology gap measured by *TECH_GAP* changes

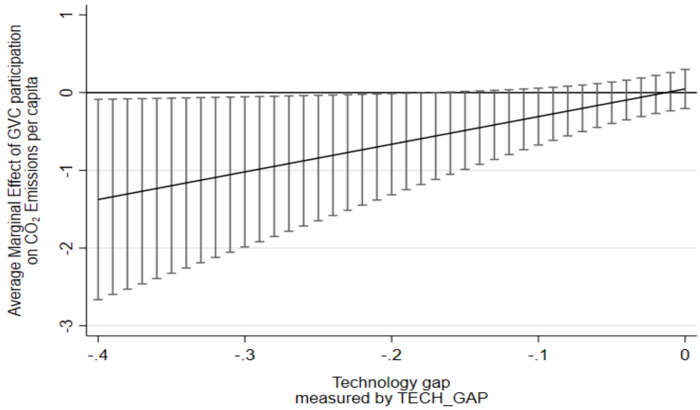


Figure 2. The average marginal effect of GVC participation on CO_2 emissions as the technology gap measured by *TECH_GAP_ENV* changes

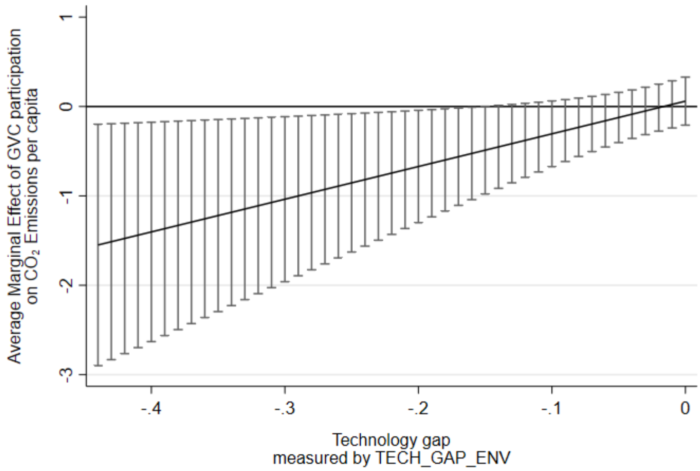


Figure 3. The average marginal effect of GVC participation on CO_2 emissions as the technology gap measured by *TECH_GAP_ST* changes

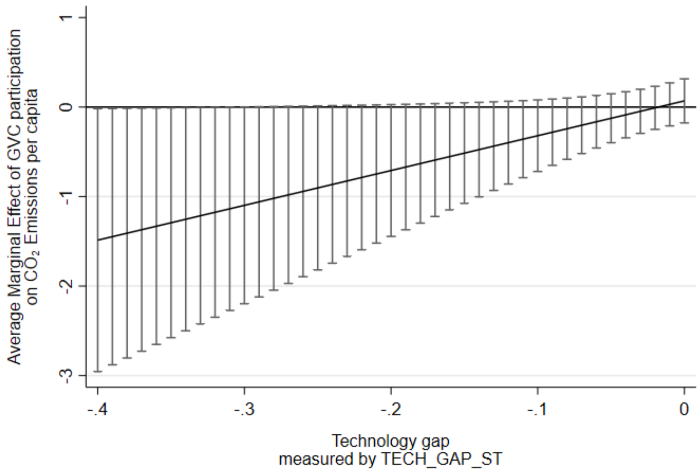
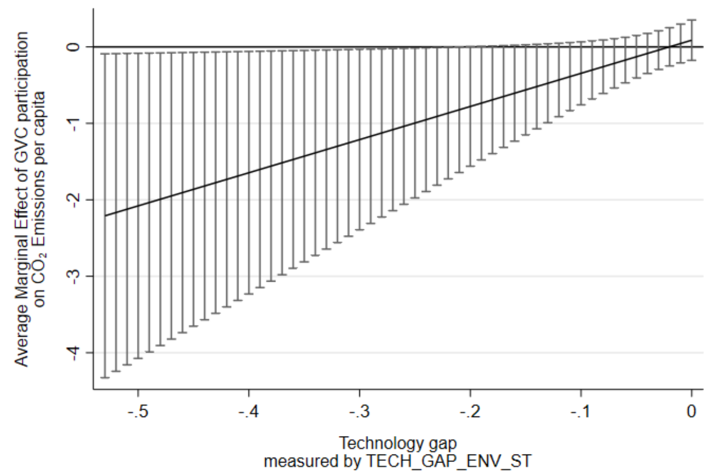


Figure 4. The average marginal effect of GVC participation on CO_2 emissions as the technology gap measured by *TECH_GAP_ENV_ST* changes



Appendix

List of emerging and developing countries used in the study (classification according to the International Monetary Fund):

Albania, Algeria, Angola, Argentina, Armenia, Azerbaijan, Bangladesh, Belarus, Benin, Bolivia, Bosnia and Herzegovina, Botswana, Brazil, Brunei Darussalam, Bulgaria, Cambodia, Cameroon, Chile, China, Colombia, the Republic of the Congo, Costa Rica, Côte d'Ivoire, Croatia, the Dominican Republic, Ecuador, Egypt, El Salvador, Eritrea, Ethiopia, Gabon, Georgia, Ghana, Guatemala, Haiti, Honduras, Hungary, India, Indonesia, Iran, Iraq, Jamaica, Jordan, Kazakhstan, Kenya, Kyrgyzstan, Lebanon, Libya, Malaysia, Mexico, Mongolia, Montenegro, Morocco, Mozambique, Myanmar, Namibia, Nepal, Nicaragua, Niger, Nigeria, North Macedonia, Pakistan, Panama, Paraguay, Peru, the Philippines, Poland, Romania, the Russian Federation, Saudi Arabia, Senegal, Serbia, South Africa, Sri Lanka, Suriname, Tajikistan, Tanzania, Thailand, Togo, Trinidad and Tobago, Tunisia, Turkey, Ukraine, the United Arab Emirates, Uruguay, Uzbekistan, Venezuela, Vietnam, Yemen, Zambia.