EXAMINING THE RELATIONSHIP BETWEEN EXPORTS AND CO_2 EMISSIONS IN VIETNAM

NGHIÊN CỨU MỐI QUAN HỆ GIỮA XUẤT KHẨU VÀ PHÁT THẢI CO_2 TẠI VIỆT NAM

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Abstract - This study examines the relationship between exports and CO_2 emissions in Vietnam from 1990 to 2022 using time-series data and the Autoregressive Distributed Lag (ARDL) model. Results indicate that, GDP growth significantly increases CO_2 emissions, while no evidence supports the Environmental Kuznets Curve in the Vietnamese context. Sectoral impacts vary: textile exports are associated with higher emissions, whereas agricultural and forestry exports contribute to emission reduction. Short- and long-run effects differ across sectors, with the ECM term indicating rapid adjustment to long-run equilibrium after short-term shocks. These findings suggest policy directions for sustainable development, including promoting green technology adoption in high-emission export sectors and supporting agriculture and forestry to ensure that export-led growth aligns with climate change mitigation goals.

Key words - CO_2 emissions; EKC theory; Exports; Sustainable Development; SDGs

Tóm tắt - Nghiên cứu này xem xét mối quan hệ giữa xuất khẩu và phát thải CO_2 tại Việt Nam từ 1990 đến 2022, sử dụng dữ liệu chuỗi thời gian và mô hình Tự hồi quy phân phối trễ (ARDL). Kết quả cho thấy, tăng trưởng GDP làm gia tăng đáng kể phát thải CO_2, trong khi không tìm thấy bằng chứng ủng hộ giả thuyết Đường cong Kuznets trong bối cảnh Việt Nam. Tác động theo ngành có sự khác biệt: xuất khẩu dệt may gắn liền với mức phát thải cao hơn, trong khi xuất khẩu nông, lâm sản góp phần giảm phát thải. Tác động ngắn hạn và dài hạn cũng khác nhau giữa các ngành với hệ số ECM cho thấy tốc độ điều chỉnh nhanh về cân bằng dài hạn sau các cú sốc ngắn hạn. Các kết quả này gợi ý định hướng chính sách phát triển bền vững, bao gồm thúc đẩy ứng dụng công nghệ xanh trong các ngành xuất khẩu phát thải cao và hỗ trợ nông, lâm nghiệp nhằm đảm bảo tăng trưởng kinh tế định hướng xuất khẩu gắn với mục tiêu giảm thiểu biến đổi khí hậu.

Từ khóa - Phát thải CO_2; Lý thuyết EKC; Xuất khẩu; Phát triển bền vững; SDGs

1. Introduction

In the context of globalization and international economic integration, exports play a crucial role in promoting economic growth in nations, particularly in developing countries such as Vietnam [1]. Export activities not only help Vietnam enhance its international standing but also serve as a primary engine for the development of its industrial, agricultural, and service sectors. However, alongside these economic benefits, the increase in export activities also brings significant environmental challenges, particularly in terms of CO_2 emissions.

The Environmental Kuznets Curve (EKC) theory posits that in the early stages of economic development, pollution levels tend to rise as national income increases [2]. However, once income exceeds a certain threshold, countries begin to invest in clean technologies and environmental protection policies, leading to a reduction in pollution [3]. This relationship has been widely studied around the world, especially in developed nations where research shows a shift from high levels of pollution to improved environmental quality as the economy reaches advanced stages of development. However, the applicability of the EKC hypothesis to addressing global externalities remains uncertain. This uncertainty largely stems from rational free-riding tendencies and the challenges associated with internalizing global externalities [4]. For instance, [5] verified the presence of the EKC in MENA countries over the period from 1990 to 2018, while [6] observed that the EKC holds true in Japan and Korea, yet not in China. Similarly, investigations by [7] in EU nations and by [8] in emerging economies did not validate the EKC relationship.

Globally, achieving a harmonious balance between enhancing global commerce and addressing environmental challenges is vital to cut CO_2 emissions and advance sustainable practices, as exemplified by the Sustainable Development Goal 13: Climate Action [9]. Therefore, the relationship between exports and CO_2 emissions has been extensively investigated in the context of robust globalization and international trade. Numerous studies indicate that exports influence emission levels through global supply chains, particularly when products are manufactured in countries that employ outdated technologies and depend on fossil fuels [10]. For instance, in China, the export of energy-intensive industrial products such as steel and cement has been associated with high CO_2 emissions [11].

Furthermore, according to [12], exports can generate an emissions leakage effect, wherein developed countries indirectly bear responsibility for high CO_2 emissions by importing products from developing economies, even though they are not directly involved in production. This highlights the importance of establishing international cooperation mechanisms and border adjustment policies to mitigate environmental impacts. For developing countries such as Brazil, exports from energy-intensive industries with limited application of green technologies further exacerbate CO_2 emissions [13]. Therefore, improving production efficiency and implementing stringent environmental policies are essential to limit the negative impacts on the global climate.

Vietnam is currently one of the countries most strongly affected by climate change, while simultaneously experiencing rapid export growth within the region. In response to global climate change and in alignment with international efforts, Vietnam has made a strong political commitment to reduce greenhouse gas emissions. Notably, at the COP26 conference in 2021, the Vietnamese government pledged to achieve net-zero carbon emissions by 2050. This commitment reflects Vietnam's intention to integrate economic development with environmental sustainability and aligns with global climate goals under the Paris Agreement [14]. Compared with other developing countries such as India and Indonesia, which also face similar trade-offs between export-driven growth and environmental sustainability, Vietnam's dual challenge of sustaining high export performance while reducing emissions underscores the urgency and importance of further academic inquiry into this topic.

Research in Vietnam has indicated that production, processing, and transportation activities related to exports are significant sources of CO_2 emissions [15]. Key export sectors such as textiles, wood processing, and fisheries play a vital role in Vietnam's economy; however, the production processes in these sectors are often highly energy-intensive [16]. Operations such as fabric processing and dyeing in the textile industry, as well as processing and freezing in the fisheries sector, require substantial amounts of fossil fuel energy, leading to considerable CO_2 emissions [17]. Nonetheless, domestic studies have primarily focused on assessing the energy consumption of these sectors without delving into detailed analyses of CO_2 emissions. Consequently, in Vietnam, the relationship between exports and CO_2 emissions has not been comprehensively investigated, thereby limiting the ability to assess the environmental impacts of export-promotion policies.

This study addresses the existing research gap by conducting a disaggregated analysis of Vietnam's export sectors in relation to CO_2 emissions. Instead of relying on aggregate export data, the study separates total exports into specific subgroups, including textiles, footwear, electronic components, agricultural products, forestry products, fisheries, and crude oil. This sector-specific approach enables a more precise investigation of how different export industries contribute to environmental degradation, uncovering heterogeneity in the emissions intensity of each sector insights that are often masked in aggregate-level analyses. By identifying which sectors are more carbon-intensive, the research provides nuanced evidence that supports the formulation of targeted and effective environmental and trade policies. Evaluating the relationship between disaggregated exports and CO_2 emissions is therefore essential for clarifying the environmental impacts of export activities, offering a scientific foundation for sustainable development strategies. In doing so, the study not only helps Vietnam optimize the economic benefits of exports but also contributes to reducing greenhouse gas emissions and achieving its international climate commitments. Furthermore, the integration of time series models to test the EKC theory, combined with sector-level disaggregation, marks an important methodological advancement, deepening the understanding of sustainable development in Vietnam.

2. Data

In this study, data were collected from the World Development Indicator (WDI) of the World Bank and the General Statistics Office of Vietnam (CSO) for the period from 1990 to 2022.

Gross Domestic Product (GDP) is measured using the 2015 base year and is expressed in billions of USD; total export production of textiles (DM); total export production of footwear (GD); total export production of electronic components (LK); total export production of agricultural products (NS); total export production of forestry products (LS); total export production of fisheries (TS); and total export production of crude oil (DT) are all measured in terms of export value in billions of USD. CO_2 emissions (CO_2) are quantified as the total emissions from all sources, measured in thousands metric tons.

3. Methodology

3.1. Long and Short-run test

To determine the long-term relationship between CO_2 emissions and economic-trade factors in Vietnam, this study employs the Autoregressive Distributed Lag (ARDL) model. The ARDL model was chosen for several practical and theoretical reasons. Firstly, ARDL can accommodate variables with different orders of integration I(0) and I(1), thus it does not require all variables in the model to have the same integration order. This is particularly useful when the data in this study may exhibit varying integration characteristics.

Furthermore, the ARDL model allows for the simultaneous estimation of both the long-run relationship and the short-run dynamics of the system. By separating the long-run relationship from the short-run dynamics and incorporating an Error Correction Model (ECM), it is possible to understand not only the factors affecting CO_2 emissions in the long term but also how the system responds immediately to temporary shocks. This is a significant advantage when investigating the complex interrelationships among economic growth, export structure, and environmental pollution. Moreover, given that the sample size in this study is relatively small, the ARDL model is an appropriate choice as it facilitates stable and efficient estimation even with a limited number of observations.

The basic form of the ARDL model is represented as follows:

$$Y_t = \alpha + \beta_1 Y_{(t-1)} + \beta_2 Y_{(t-2)} + \cdots + \beta_p Y_{(t-p)} + \delta X_t + \gamma_1 X_{(t-1)} + \gamma_2 X_{(t-2)} + \ldots + \gamma_q X_{(t-q)} + \varepsilon_t$$

where, Y_t denotes the dependent variable at time t, whereas X_t stands for one or several independent variables observed at the same point in time. The terms $Y_{(t-1)}, Y_{(t-2)} \ldots Y_{(t-p)}$ represent the lagged values of the dependent variable, indicating its autoregressive characteristics. Similarly, $X_{(t-1)}, X_{(t-2)} \ldots X_{(t-q)}$ capture the lagged influences of the independent variables, reflecting their distributed lag effects. The parameters $\alpha, \beta_1, \beta_2 \ldots \beta_p, \delta, \gamma_1, \gamma_2 \ldots \gamma_q$ are estimated to quantify the short-run and long-run dynamics among the variables. The error term ε_t accounts for the unexplained variation in the dependent variable.

Accordingly, the basic linear model is specified as follows:

$$lnCO2_t = \alpha_1 + \sum_{i=0}^{p} \beta_0 lnCO_{2_{t-i}} + \sum_{j=0}^{q1} \beta_1 lnGDP_{t-j} + \sum_{j=0}^{q2} \beta_2 lnDM_{t-j} + \sum_{j=0}^{q3} \beta_3 lnGD_{t-j} + \sum_{j=0}^{q4} \beta_4 lnLK_{t-j} + \sum_{j=0}^{q5} \beta_5 lnNS_{t-j} + \sum_{j=0}^{q6} \beta_6 lnLS_{t-j} + \sum_{j=0}^{q7} \beta_7 lnTS_{t-j} + \sum_{j=0}^{q8} \beta_8 lnDT_t + \varepsilon_t$$

Subsequently, following [18], the squared term of GDP is incorporated into this study to allow for testing of the EKC hypothesis. The quadratic model is thus expressed as:

$$lnCO2_t = \alpha_2 + \sum_{i=0}^{p} \gamma_0 lnCO_{2_{t-i}} + \sum_{j=0}^{q1} \gamma_1 lnGDP_{t-j} + \sum_{j=0}^{q1} \gamma_{1s} lnGDP_{t-j}^2 + \sum_{j=0}^{q2} \gamma_2 lnDM_{t-j} + \sum_{j=0}^{q3} \gamma_3 lnGD_{t-j} + \sum_{j=0}^{q4} \gamma_4 lnLK_{t-j} + \sum_{j=0}^{q5} \gamma_5 lnNS_{t-j} + \sum_{j=0}^{q6} \gamma_6 lnLS_{t-j} + \sum_{j=0}^{q7} \gamma_7 lnTS_{t-j} + \sum_{j=0}^{q8} \gamma_8 lnDT_t + \varepsilon_t$$

The residuals from these models, specifically the extracted error correction term, will be employed to construct an ECM that captures the short-run dynamics among the variables. The ECM acknowledges the existence of a stable long-run relationship among the variables through the concept of cointegration while allowing for short-run adjustments toward equilibrium. This feature makes the ECM particularly suitable for situations where variables experience short-run fluctuations but tend to revert to a long-run equilibrium. In addition, the ECM facilitates the interpretation of parameters such as the speed of adjustment toward equilibrium, which helps elucidate the underlying dynamics. Empirical evidence supporting this application can be found in the research of [19], who demonstrated the effectiveness of ECM in estimating both short- and long-run coefficients in macroeconomic relationships.

The basic ECM equation is as follow:

$$\Delta Y_t = \alpha\left(\beta_0 - Y_{(t-1)}\right) + \sum \beta_i \Delta x_{(t-i)} + \varphi ECT_{(t-1)} + \varepsilon_t$$

where, ΔY_t indicates the change in the dependent variable Y at time t, while $Y_{(t-1)}$ represents its lagged value. The term $\Delta x_{(t-i)}$ captures the change in the independent variable x at time t with a lag of i. The parameter α corresponds to the coefficient of the error correction component. The coefficients β_i are associated with the lagged differences of the independent variable, reflecting short-term dynamics. The term $\varphi ECT_{(t-1)}$ represents the coefficient of the error correction term, which reflects the rate at which the system returns to its long-term equilibrium. Lastly, ε_t accounts for the error term or disturbance in the model.

3.2. Stationarity test

Various unit root tests exist to assess stationarity, including the Dickey-Fuller test and its augmented version, the ADF test by [20], which expands on the basic test by incorporating lagged differences to address serial correlation. In this study, all variables are subjected to rigorous stationarity testing to confirm that their statistical properties are consistent over time. Given its robust performance in finite samples and its widespread acceptance in econometric research, the ADF test has been selected as the primary tool for assessing stationarity. The results obtained from the ADF test provide a solid foundation for subsequent model estimations and ensure the reliability of the findings derived from the cointegration analysis. The results should confirm that all variables are integrated at I(0) or I(1), with none being I(2) to satisfy the fundamental condition for applying the ARDL model. The ADF test equation is illustrated as below:

$$\Delta Y_t = \alpha + \beta_t + \gamma Y_{(t-1)} + \sum_{i=1}^{p} \Delta Y_{(t-i)} + \varepsilon_t$$

Where, Δ denotes the first-difference operator, and $Y_{(t-1)}$ refers to the lagged value of the time series variable. The term α represents the intercept, while β_t is the coefficient of the time trend, capturing the existence of a linear trend over time. The parameter γ corresponds to the coefficient of the lagged level of the variable. The expression $\sum_{p}^{i=1} \Delta Y_{(t-i)}$ includes the autoregressive components of the differenced series, accounting for the influence of past changes. Finally, ε_t denotes the error term, representing the unexplained portion of the variation.

3.3. Optimal Lag Length test

In this study, to determine the optimal lag order for the variables in the ARDL model, the Akaike Information Criterion (AIC) developed by [21] will be employed. The model with the lowest AIC value indicates the optimal lag structure, balancing model accuracy and complexity, thereby ensuring the stability and efficiency of the estimates in the analysis and enhancing the overall precision of the statistical tests. The AIC is employed instead of other methods such as the Bayesian Information Criterion (BIC) for several reasons followed the research of [22]. First, AIC tends to be less conservative than BIC, which allows for the selection of slightly longer lag lengths that capture the system's dynamic behavior more comprehensively. Second, given the finite sample size utilized in this research, AIC demonstrates superior performance in model selection by reducing the risk of mis-specifying the dynamic structure. Finally, AIC is grounded in information theory principles and offers a more straightforward interpretation, thereby facilitating clearer and more coherent exposition of the modeling results.

3.4. Bounds test

The Bound test proposed by [23] is employed to evaluate the existence of cointegration among variables, a critical prerequisite for ARDL analysis. Cointegration indicates a long-term equilibrium relationship among non-stationarity variables, thereby helping to ascertain whether the ARDL framework is appropriate for subsequent investigation. This test involves estimating an auxiliary regression, known as the Bounds F-test, based on an ECM. The ECM may be specified as follows:

$$Y_t = \alpha_0 + \delta_1 X_{1(t-1)} + \delta_2 X_{2(t-1)} + \cdots + \delta_n X_{n(t-1)} + \sum_{i=1}^{k1} \emptyset_i \Delta X_{1(t-i)} + \sum_{j=1}^{k2} \omega_j \Delta X_{2(t-j)} + \cdots + \sum_{l=1}^{kn} \varphi_l \Delta X_{n(t-l)} + \varepsilon_t$$

Where, $\delta_1, \delta_2 \dots \delta_n$ denote the long-run multipliers, while $k_1, k_2 \dots k_n$ represent the optimal lag lengths assigned to each respective variable. The parameter α_0 represents the drift term, while ε_t denotes the stochastic error component. To assess the existence of a long-run relationship, an F-test is conducted based on the following hypotheses:

H_0: $\delta_1 = \delta_2 = \ldots = \delta_n = 0$

H_1: $any\ \delta_i \neq 0\ (i = 1, 2 \dots n)$

4. Results and Discussions

4.1. Correlation test

The Spearman correlation matrix among the variables reveals a clear association between most of the variables in the model. The variables CO_2, GDP, DM, GD, LK, NS, and TS exhibit high correlation coefficients, indicating a strong positive co-movement. This suggests that the level of CO_2 emissions is closely linked to key economic indicators and major export activities. Conversely, the variable DT displays a negative correlation with CO_2, reflecting the distinct characteristics of crude oil compared to the other sectors.

Table 1. *Spearman Correlation Test Results*

	CO_2	GDP	DM	GD	LK	NS	LS	TS	DT
CO_2	1.000								
GDP	0.997	1.000							
DM	0.995	0.998	1.000						
GD	0.996	0.999	0.999	1.000					
LK	0.977	0.980	0.977	0.979	1.000				
NS	0.982	0.989	0.989	0.989	0.983	1.000			
LS	0.927	0.931	0.931	0.930	0.936	0.919	1.000		
TS	0.989	0.993	0.993	0.993	0.982	0.987	0.934	1.000	
DT	-0.263	-0.266	-0.267	-0.266	-0.298	-0.271	-0.399	-0.274	1.000

Note: GDP: Gross Domestic Product. DM: Textile exports; GD: Footwear exports; LK: Electronics component exports; NS: Agricultural exports; LS: Forestry exports; TS: Fisheries exports; DT: Crude Oil exports. CO2: CO_2 emissions

4.2. Stationarity test

The ADF test results indicate that most variables have non-stationarity at the level (I(0)) but have stationarity after first differencing (I(1)). Specifically, lnGD exhibits a t-statistic and p-value that suggest it has stationarity at the level. These results confirm that the dataset comprises a combination of I(0) and I(1) variables. Importantly, none of the variables are integrated at I(2), which is a crucial condition for the validity of the ARDL bounds testing approach. Therefore, the integration properties of the variables fully satisfy the requirements for applying the ARDL model, ensuring the robustness and reliability of the subsequent cointegration and dynamic estimations.

Table 2. *ADF Stationarity Test Results*

	t-statistic		t-statistic
lnCO2	-1.408	lnNS	-1.438
d.lnCO2	-3.718***	d.lnNS	-4.280***
lnGDP	-2.41	lnLS	0.65
d.lnGDP	-5.644***	d.lnLS	-5.292***
lnDM	-2.584*	lnTS	-1.303
d.lnDM	-5.017***	d.lnTS	-5.206***
lnGD	-4.419***	lnDT	0.181
lnLK	-0.081	d.lnDT	-4.219***
d.lnLK	-6.158***		

*Note: ***, **, and * stand for statistical significance at 1%, 5%, and 10% levels, respectively*

4.3. Bounds test

The bounds test results for both the linear and quadratic models indicate that the F-statistics in both cases exceed the upper critical bound at the 1% significance level. This allows us to reject the null hypothesis of no cointegration, thereby confirming the existence of a long-run relationship among the variables in both models.

Table 3. *Bounds Test Results*

	Linear Model	Quadratic Model
Optimal lag	1,0,0,1,0,1,1,1,1	1,0,0,0,1,0,1,1,1,1
F-statistic	5.304***	4.508***
	Critical Bounds	
Sig. Level	**I (0)**	**I (1)**
1%	2.79	4.10
5%	2.22	3.39
10%	1.95	3.06

*Note: ***, **, and * stand for statistical significance at 1%, 5%, and 10% levels, respectively*

4.4. Long-run test

Table 4. *Long-run Test Results (dependent variable: lnCO_2)*

Variable	Linear Model		Quadratic Model	
	Coeff	***t*-value**	**Coeff**	***t*-value**
lnGDP	0.572***	3.54	0.731	0.90
lnGDP²			-0.007	-0.20
lnDM	0.349***	2.88	0.363***	2.50
lnGD	0.025	0.36	0.014	0.16
lnLK	0.084*	1.75	0.087	1.68
lnNS	-0.397***	-4.05	-0.407***	-3.61
lnLS	-0.257***	-2.89	-0.251***	-2.55
lnTS	0.115	1.38	0.115	1.32
lnDT	-0.254***	-4.76	-0.261***	-4.06
R^2	0.766		0.767	
Adj. R^2	0.573		0.548	
Durbin-Watson	1.984		1.983	
White test (p)	0.614		0.555	

*Note: ***, **, and * stand for statistical significance at 1%, 5%, and 10% levels, respectively*

In the long run, GDP has a significant positive effect on CO_2 emissions in the first-order model, whereby an increase in GDP is associated with a corresponding rise in CO_2 emissions, reflecting intensified industrialization and increased fossil fuel consumption. However, when examining the second-order model with the squared GDP term, the results indicate that the coefficient on the squared term is not statistically significant. In other words, there is no evidence supporting the existence of the EKC hypothesis in Vietnam, as the relationship between GDP and CO_2 in the sample remains monotonically increasing. These findings are consistent with previous studies [18], which also concluded that the relationship between income and pollution in Vietnam is linearly positive in both the short and long run.

The expansion of the textile industry exhibits a positive long-run coefficient, implying that the development of this sector contributes to increased CO_2 emissions. This is consistent with the reality that the textile industry is energy-intensive and heavily reliant on chemicals, leading to high levels of pollution. These results are in line with other studies, such as [24], which found that in developing countries, economic growth is closely associated with high fossil fuel consumption. Conversely, the negative correlation observed with the crude oil variable aligns with previous research as of [25]. Countries like Vietnam export crude oil, which is then processed and consumed elsewhere, leading to CO_2 emissions occurring outside the exporting country. This aligns with findings by [26], who noted that developed countries often import carbon-intensive goods, effectively outsourcing their emissions to developing nations. Moreover, [27] found that in certain contexts, natural resource exports can help decouple economic growth from environmental degradation, especially when accompanied by strong institutional frameworks and reinvestment into sustainable sectors. Therefore, the negative long-run effect observed may reflect structural characteristics of Vietnam's trade composition and energy use patterns. Additionally, structural changes and technological improvements within Vietnam's crude oil sector could contribute to reduce domestic emissions intensity. As of the research of [28] has shown that modernization of extraction and processing technologies, increased energy efficiency, and shifts toward cleaner energy sources may have mitigated emissions.

In contrast, output from the agricultural and forestry sectors exerts a negative influence on CO_2 emissions. As the production value in these sectors increases, CO_2 emissions tend to decline, suggesting that the development of agriculture and forestry may help absorb or offset a portion of the emissions. One explanation is that increased agricultural productivity limits the expansion of cultivated land, thereby protecting forests, which act as natural carbon sinks. Moreover, improved forest management and expansion enhance the CO_2 absorption capacity of forest ecosystems. This trend is consistent with previous studies as of [29], which also noted that enhancing the value of agricultural outputs contributes to reducing CO_2 emissions through the carbon sequestration capabilities of vegetation and soil.

4.5. Short-run test

Table 5. *Short-run Test Results (dependent variable: ΔlnCO_2)*

Variable	Linear Model		Quadratic Model	
	Coeff	***t*-value**	**Coeff**	***t*-value**
ΔlnGDP	-0.103	-0.54	-0.774	-0.59
ΔlnGDP²			0.034	0.51
ΔlnDM	-0.104	-0.47	-0.113	-0.42
ΔlnGD	-0.338**	-2.75	-0.337**	-2.65
ΔlnLK	-0.062	-1.01	-0.067	-1.02
ΔlnNS	0.251*	1.92	0.246*	1.81
ΔlnLS	0.155**	2.3	0.149*	1.97
ΔlnTS	-0.230**	-2.18	-0.219*	-1.80
ΔlnDT	0.153**	2.02	0.153*	1.97
ECM_{t-1}	0.766		0.767	
R^2	0.573		0.548	
Adj. R^2	1.984		1.983	
Durbin-Watson	0.614		0.555	
White test (p)	0.766		0.767	

*Note: ***, **, and * stand for statistical significance at 1%, 5%, and 10% levels, respectively*

In the short-run dynamics, the independent variables are incorporated in first differences to capture their immediate impact on CO_2 emissions. Specifically, the footwear export sector demonstrates that when output experiences temporary fluctuations, the production system responds swiftly by adjusting to reduce CO_2 emissions potentially through the adoption of modern technology and advanced production processes.

Conversely, although the agricultural export sector exerts a reducing effect on emissions in the long run, in the short run, output fluctuations may slightly stimulate CO_2 emissions, as agricultural enterprises typically operate under traditional processes and do not promptly react to minor changes. Similarly, the forestry export sector tends to exhibit a temporary increase in emissions when processing, transportation, or storage activities surge before comprehensive improvements are implemented.

In the fisheries export sector, short-run fluctuations have an inverse effect, indicating that the immediate adoption of energy-efficient processing methods helps to lower CO_2 emissions in the short term. Additionally, energy efficiency-related factors also show the capacity for rapid adjustment, albeit with modest intensity. While crude oil shows a negative impact on CO_2 emissions in the long run due to Vietnam mainly exporting raw materials and technological improvements, the short-run effect is positive because increased extraction and production activities locally raise emissions before these long-run benefits materialize.

Notably, the ECM coefficient reveals that any deviation from the long-run equilibrium is robustly corrected in the subsequent period, reflecting the sensitivity of Vietnam's economic-environmental system in absorbing minor shocks and mitigating their negative impact on emissions.

4.6. VIF analysis

Table 6. *Multicollinearity Diagnostics Results by VIF analysis*

	VIF Value	
Variable	**Linear Model**	**Quadratic Model**
lnGDP	2.24	7.89
lnGDP²		7.83
lnLS	2.75	3.57
lnGD	2.33	3.31
lnDT	2.28	3.47
lnNS	2.18	3.42
lnLK	2.17	3.08
lnTS	1.41	2.91
lnDM	1.35	2.24
Mean VIF	**2.09**	**6.08**

In the linear model, all explanatory variables exhibit VIF values well below 5, with a mean VIF of 2.09, indicating an absence of multicollinearity concerns and ensuring stable and reliable coefficient estimates. In the quadratic model, although lnGDP and $lnGDP^2$ have VIFs of 7.89 and 7.83, respectively, these values remain below the commonly accepted upper threshold of 10 [30]. The slight increase is expected due to the inclusion of $lnGDP^2$, which is inherently correlated with lnGDP. This form of structural moderate multicollinearity is typical in polynomial regression models and does not imply model misspecification [31]. The remaining variables in the quadratic model maintain low VIFs. Thus, the VIF results affirm the empirical validity of both model specifications, with multicollinearity remaining within tolerable bounds.

5. Conclusion and Recommendations

The results indicate that the relationship between export activities, economic growth and CO_2 emissions in Vietnam is multifaceted, reflecting the complexity of the production structure and the extent to which green technology is implemented. In the long term, economic expansion evidenced by GDP growth coupled with increased energy consumption and production leads to higher CO_2 emissions. Concurrently, export sectors play a crucial role in shaping emission levels: industries that rely on traditional technologies, such as textiles and apparel, have contributed to increased emissions, while sectors with production processes that are less energy-intensive, such as agriculture and forestry, tend to reduce CO_2 emissions. Other export sectors, such as footwear and electronic components, exhibit heterogeneous impacts, reflecting varying degrees of technological advancement and the implementation of different energy-saving measures across industries.

In the short term, although temporary fluctuations in the production activities of export sectors may generate immediate effects on CO_2 emissions, these effects are generally weak and are dampened by the self-regulatory mechanisms inherent in the economic-environmental system. The ECM coefficient demonstrates that the system is capable of rapid adjustment when it deviates from its long-term equilibrium, thereby mitigating the impact of short-term shocks. This suggests that, although export sectors may induce short-term fluctuations in emission levels, their cumulative effects are more pronounced in the long-term relationship.

Based on these findings, it is imperative to implement coordinated intervention strategies to promote green economic development. Specifically, the transfer of modern technology and the improvement of production processes are essential to reduce energy consumption in key industries, such as textiles and apparel, which have been identified as having a clear impact on increasing emissions. Simultaneously, supporting and encouraging the development of traditional sectors, such as agriculture and forestry which have demonstrated a pollution-reducing effect will help sustain and enhance environmental protection efforts. Moreover, strengthening environmental monitoring and forecasting mechanisms is necessary to promptly address short-term fluctuations and maintain a sustainable equilibrium in the economic-environmental system. When these policies are implemented in a coordinated manner, they will contribute to reducing greenhouse gas emissions and foster the sustainable development of Vietnam's economy in the future.

While this study provides empirical evidence on the relationship between exports and CO_2 emissions within an ARDL framework, future research should address potential endogeneity concerns, such as reverse causality between CO_2 emissions and exports, or the omission of relevant factors like foreign direct investment (FDI), urbanization, and technological progress that may influence both economic activity and environmental outcomes. Due to data limitations, robustness checks could not be conducted in this study, but these limitations are acknowledged and offer meaningful avenues for future investigation. Further research could also broaden the scope by examining additional types of pollutants or particulate matter to provide a more comprehensive picture of environmental degradation. Moreover, the use of alternative modeling techniques including dynamic panel data models, nonlinear estimators, or machine learning approaches could better capture complex relationships and improve predictive accuracy. Cross-country comparative analyses would also enhance the generalizability of findings and offer deeper insights into the heterogeneity of the growth-emissions nexus.

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