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The impact of industrialization on environmental quality and the environmental Kuznets Curve in Vietnam: A nonlinear and asymmetric analysis using ARDL and QQR approaches

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ABSTRACT

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This study examines the dynamic relationship between Vietnam's ecological footprint, economic growth, and industrial production during its period of rapid industrialization and pursuit of sustainable development. The purpose is to test the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation worsens in the early stages of growth but improves once income reaches a certain threshold. Using annual data from 1987 to 2023, the study investigates how industrialization affects environmental quality at different stages of development. The autoregressive distributed lag (ARDL) and quantile-on-quantile regression (QQR) models are employed to capture both short- and long-run relationships, as well as nonlinear and asymmetric effects among variables. The findings confirm a long-run cointegrating relationship among ecological footprint, GDP, and industrial production. Economic growth initially increases environmental pressure but shows signs of an EKC turning point at higher income quantiles. Industrial production has a dual effect: when pollution levels are low, it contributes to improving environmental quality through technological progress, while at higher pollution levels, it intensifies environmental degradation. These results emphasize that the growth–environment relationship in Vietnam is nonlinear and stage-dependent. Practical implications include promoting the adoption of green technologies, developing eco-industrial parks, integrating environmental goals into industrial policies, and designing adaptive strategies consistent with Vietnam's commitment to achieving net-zero emissions by 2050.

Contribution/Originality: This study contributes to the existing literature by applying ARDL and quantile-on-quantile regression (QQR) methods to capture short- and long-term effects, as well as nonlinear and asymmetric relationships between industrialization, economic growth, and ecological footprint. It is one of the studies validating the ecological footprint-based Environmental Kuznets Curve for a developing economy.

1. INTRODUCTION

Over the past three decades, Vietnam has achieved many accomplishments in growth, with GDP reaching 8.02% in 2022 and 7.09% in 2024 (Vu & Nguyen, 2025). The industrial sector plays a key role, with the industrial production index (IPI) in the first 11 months of 2024 increasing by 8.4%, and the technology industry revenue alone exceeding 152 billion USD (Bao, 2024; Ngọc, 2024). However, urbanization and industrialization have led to environmental pollution, as Hanoi's air quality index has frequently exceeded hazardous levels (Gia, 2024), or Ho Chi Minh City can treat only 31% of its more than 10,000 tons of daily waste (Đông, 2024).

Ecological Footprint (EF) is a synthetic index that reflects the totality of human activities on biological resources (Wackernagel, Lin, Evans, Hanscom, & Raven, 2019). Many studies have used the EF index to test the Environmental Kuznets hypothesis (EKC) (Ansuategi, Barbier, & Perrings, 1998). However, some studies have confirmed the EKC hypothesis (inverted U-shaped), while other studies have not confirmed the EKC hypothesis and show a linear or unclear relationship (Li & Zhang, 2025; Nosheen, Iqbal, & Ahmad, 2023). Studies by, such as Nguyen et al. (2024) have verified the existence of EKC in Vietnam, and the actual data show that Vietnam's EF continues to increase, reflecting in detail the impact of industrial products and polluted environments (Gia, 2024; Guarascio, 2024; Vu & Nguyen, 2025). However, the asymmetric impacts of industrial production on the environment have not been clearly quantified.

Thus, the use of the ecological footprint is a more comprehensive index than the CO_2 index, especially in Vietnam. In addition, the impact of industrial production on environmental quality in a non-linear direction has not been clarified. In response to that gap, the article analyzes the relationship between ecological footprint (representing environmental quality) with economic growth and industrial production in Vietnam during the period 1987–2023, using a combination of autoregressive distributed lag (ARDL) and quartile regression (QQR) models. The next section will present the theoretical basis and rationale for selecting the variables EF, GDP, and industrial production in the research model.

The theoretical basis of environmental quality and economic growth: The Kuznets Curve hypothesis, which describes the nonlinear relationship between economic growth and income inequality, was first introduced in 1955 by Kuznets (1955). Later, Grossman and Krueger (1991) extended this theory to environmental economics by analyzing the relationship between economic growth and environmental pollution, which commonly takes an inverted U-shaped curve form (Bucak, Önder, & Çatık, 2024; Shahzad & Aruga, 2024; Wang, Wang, Li, Jiang, & Xueting, 2024). In the early stages of the inverted U curve, growth increases pollution, but after reaching a high-income threshold, environmental quality improves while economic growth continues (Bucak et al., 2024; Wang et al., 2024). In many studies, the EKC can have an N-shape or an inverted N-shape (Villanthenkodath, Ansari, Balsalobre-Lorente, & Satrovic, 2024) or be linear in economies that have not yet reached the turning point (Caporin, Cooray, Kuziboev, & Yusubov, 2024).

Regarding the selection of factors in this study, the ecological footprint is chosen as the variable representing environmental quality, as mentioned above, because it is a comprehensive indicator that reflects the level of ecological consumption compared to biocapacity (Eufrasio & Lenny, 2024).

GDP per capita is the most commonly used variable to proxy economic growth in EKC studies, as it directly reflects the relationship between income and environmental degradation.(Omay, Yildirim, & Balta-Ozkan, 2024; Sun, Yunqiu Sun, Zhiyu Jiang, & Zhiman, 2024). Using GDP allows for consistent testing of the EKC theory across global, regional, or national-scale studies (Azam, Rehman, Khan, & Haouas, 2024; Nketiah, Adeleye, & Okoye, 2025). Both traditional models and modern approaches consider GDP per capita as the core input indicator for measuring the level of economic development (Subramaniam, Yogeeswari Loganathan, & Ariffin, 2024; Sun et al., 2024). From the theoretical framework of the EKC, GDP remains the standard measure in assessing the relationship between growth and environmental quality (Freire, da Silva, & de Oliveira, 2023; Omay et al., 2024).

The industrial production factor is included in the model due to its central role in the relationship between economic development and environmental quality (Jinapor, Abor, & Graham, 2024), and industrial production often increases environmental pollution, especially in developing countries. However, upgrading the industry towards high technology can improve environmental quality (Zhi-Qiang et al., 2024). Environmental regulations often directly impact polluting industries, such as metallurgy, and serve as a lever to promote the development of high-tech industries (Guo, Lu, & Qu, 2024). In addition, environmental policy can orient industry towards cleaner production (Xiang et al., 2024). Therefore, it is necessary to include the industrial production variable in the model to evaluate the effectiveness of environmental policies on industrial production.

The choice of EF, GDP per capita, and industry reflects a comprehensive approach, suitable for the context of industrialization in Vietnam. The EF indicator allows for a broader assessment of environmental quality compared to indicators such as CO_2, CH_4, while GDP and GDP^2 are used to directly test the EKC hypothesis. To analyze the short-run and long-run relationships as well as exploit nonlinear characteristics, the study combines the autoregressive distributed lag (ARDL) model and the quartile regression (QQR). The next section will present the research method used in detail.

2. RESEARCH METHODOLOGY

2.1. Autoregressive Distributed Lag Model

2.1.1. Model Specification

The autoregressive distributed lag model in time series consists of two parts: (i) the autoregressive component, which indicates that the dependent variable depends on its own past values, and (ii) the distributed lag component, which signifies that the independent variables influence the dependent variable over multiple lag periods.

The ARDL model was proposed by Pesaran and Shin (1999) in Equation1.

$$\text{ARDL}\,(q,p)\Delta Y_t = \beta_0 + \underbrace{\textstyle\sum_{j=1}^{p} \beta_j \Delta Y_{t-j} + \sum_{i=0}^{q} \delta_{1,i} \Delta X_{t-i}}_{\textit{Short run}} + \underbrace{\varphi_1 Y_{t-1} + \varphi_2 X_{t-1}}_{\textit{Long run}} + \varepsilon_t \qquad (1)$$

In which, short-term coefficients as: β_0; β_j; $\delta_{1,i}$; the long-run coefficients as: φ_1; φ_2 and ε_t represents the error term

The ARDL model is suitable for small sample sizes, can handle variables that are stationary at I(0) and I(1), allows for different lag lengths, and simultaneously estimates both short-run and long-run relationships within the same system of equations.

The ARDL model applied in this study is expressed in Equation 2.

$$\text{ARDL: } \Delta \ln EF_t = \beta_0 + \underbrace{\textstyle\sum_{j=1}^{p} \beta_j \ln EF_{t-j} + \sum_{i=0}^{q} \delta_{1,i} \ln GDP_{t-i} + \sum_{i=0}^{q} \delta_{2,i} \ln GDP_{t-i}^2 + \sum_{i=0}^{q} \delta_{3,i} \ln IND_{t-i}}_{\text{Short run}} + +$$

$$\underbrace{\varphi_1 \ln EF_{t-1} + \varphi_2 \ln GDP_{t-1} + \varphi_3 \ln GDP_{t-1}^2 + \varphi_4 \ln IND_{t-1}}_{\text{Long run}} + \varepsilon_t \qquad (2)$$

The model is estimated using the Ordinary Least Squares (OLS) method, with lag order p for the dependent variable and lag order q for the independent variables. The lag lengths are determined based on the Akaike Information Criterion (AIC) or the Schwarz Information Criterion (SIC). In this study, EViews software is employed to automatically select the optimal lag structure following the procedure suggested by Nsor-Ambala and Amewu (2023). The error term ε_t is assumed to have an expected value of zero and a constant variance.

2.1.2. Unit Root Test and Cointegration Test

2.1.2.1. Unit Root Test

Before estimating the ARDL model, it is essential to examine the stationarity of the variables lnEF, lnGDP, and lnIND. This study employs two widely used approaches: the Augmented Dickey–Fuller (ADF) test (Dickey & and Fuller, 1979) and the Phillips–Perron (PP) test (Phillips & Perron, 1988) to determine whether the variables are stationary at level [I(0)] or become stationary after first differencing [I(1)].

2.1.2.2. Cointegration Test

In time-series analysis, traditional cointegration tests such as Engle and Granger (1987); Johansen (1988) and Phillips and Ouliaris (1990) require all variables to be integrated in the same order. This condition can lead to bias when the model includes a mix of variables that are stationary at I(0) and I(1). To address this limitation, Pesaran and Shin (1999) proposed the Bounds Test to determine the existence of cointegration among variables. The Bounds Test is based on the F-statistic, estimated using OLS. The null and alternative hypotheses are as follows: No cointegration H₀: $\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = \varphi_5^{+} = \varphi_5^{-} = 0$ and Cointegration exists H₁: $\varphi_1 \neq \varphi_2 \neq \varphi_3 \neq \varphi_4 \neq \varphi_5^{+} \neq \varphi_5^{-} \neq 0$. If the calculated F-statistic exceeds the upper bound, cointegration is confirmed; if it falls below the lower bound, no cointegration exists; and if it lies between the bounds, the result is inconclusive.

2.1.3. Short-Run Relationship

When cointegration is established, the short-run relationship is analyzed through the Error Correction Model (ECM), which measures the speed at which the system adjusts back to its long-run equilibrium after a short-term shock (Ericsson & MacKinnon, 2002; Kremers, Ericsson, & Dolado, 1992). In this study, the ECM is expressed in Equation 3).

$$\Delta \ln EF_t = \beta_0 + \sum_{j=1}^{p} \beta_j \Delta \ln EF_{t-j} + \sum_{i=0}^{q} \delta_{1,i} \Delta \ln GDP_{t-i} + \sum_{i=0}^{q} \delta_{2,i} \Delta \ln GDP_{t-i}^{2} + \sum_{i=0}^{q} \delta_{3,i} \Delta \ln IND_{t-i} + \theta ECT_{t-1} + v_t \qquad (3)$$

The term θECT_{t-1} represents the speed of adjustment following a short-run shock, indicating how quickly the system returns to its long-run equilibrium. It is estimated using OLS, as all variables in the ECM are stationary.

2.1.4. Long-Run Relationship

In the ARDL framework, the parameters φ_i capture the long-run relationships among variables.

$$\Delta \ln CO2_t = \varphi_1 \ln CO2_{t-1} + \varphi_2 \ln GDP_{t-1} + \varphi_3 \ln GDP_{t-1}^{2} + \varphi_4 \ln RR_{t-1} + \varphi_5^{+} \ln FDI_{t-1}^{+} + \varphi_5^{-} \ln FDI_{t-1}^{-} + \varepsilon_t \qquad (4)$$

Equation 4 simultaneously quantifies the long-term effects of economic growth and industrial production on environmental quality, as measured by the ecological footprint indicator (EF).

2.2. Quantile-on-Quantile Regression (QQR) Method

The Quantile-on-Quantile Regression (QQR) approach, proposed by Sim and Zhou (2015), extends the traditional quantile regression by analyzing the relationship between two variables across the entire quantile distribution, rather than only at the median. The QQR method evaluates the impact of the τ-th quantile of an independent variable on the θ-th quantile of the dependent variable, allowing researchers to detect nonlinear and asymmetric characteristics that conventional regression techniques may overlook (Arain, Han, Sharif, & Meo, 2020; Koenker & Bassett, 1978; Qureshi et al., 2020). This method does not require the assumption of a normal distribution or homoscedasticity of errors, so it is very suitable for economic-financial data with skewed distributions or high volatility.

The traditional quantile regression model at the quantile τ, is expressed as Equation 5.

$$Y_t = \alpha(\tau) + \beta(\tau) X_t + \varepsilon_t^{\tau} \qquad (5)$$

However, this model only evaluates the effect of X_t^{τ} on the $\tau - th$ quantile of Y_t^{τ}, without considering the quantile level of X_t that generates this effect.

Therefore, this study applies the Quantile-on-Quantile Regression (QQR) approach to analyze the relationship between environmental quality, measured by the ecological footprint, $lnEF_t$ and each independent variable X_t^{τ} (including economic growth GDP_t^{τ} and industrial share IND_t^{τ}) across different pairs of quantiles (θ, τ).

The extended QQR model proposed by Sim and Zhou (2015) is presented in Equation 6.

$$y_t^{\tau} = \beta_1^{(X)}(\tau, \theta) + \beta_2^{(X)}(\tau, \theta)\left(X_t - x_t^{\theta}\right) + \varepsilon_t^{(\theta, \tau)} \qquad (6)$$

Where: y_t^{τ}: Represents the $\tau - th$ quantile of $lnEF_t$; x_t^{θ} denotes the $\theta - th$ quantile of the independent variable X_t ; $\beta_2^{(X)}(\tau, \theta)$ captures the influence of the $\theta - th$ quantile of X_t on the $\tau - th$ quantile of $lnEF_t$.

The kernel-weighted quantile regression function is defined as follows (Equation 7).

$$\hat{\beta}(\tau, \theta) = agr \min_{\beta(\tau,\theta)} \sum_{t=1}^{T} \rho_{\tau}\left(y_t - \beta_1(\tau, \theta) - \beta_2(\tau, \theta)\left(x_t - x_t^{\theta}\right)\right) K\left(\frac{x_t - x_t^{\theta}}{h}\right) \qquad (7)$$

Where:

$\rho_{\tau}(u) = u\left(\tau - I(u < 0)\right)$: is the check function, and

$K(\cdot)$ – is the kernel function, which serves as a weighting mechanism that assigns influence to nearby observations when estimating the regression at each specific quantile. In this study, the Gaussian kernel is used to smooth the data in the quantile-on-quantile space, allowing assessment of how the $\theta - th$ Quantile of the independent variable affects the $\tau - th$ quantile of the dependent variable.

The Gaussian kernel function is expressed as.

$$K(u) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{u^2}{2}\right)$$

Where: $u = \frac{x_t - x_t^\theta}{h}$ represents the standardized deviation between the observed value and the quantile being analyzed, and h denotes the bandwidth parameter.

The Gaussian kernel is selected for its continuity, smoothness, and full-domain definition, making it well-suited for models with nonlinear structures such as QQR. To choose the bandwidth *h*, the study used the standard formula of Silverman (1986) as follows:

$$h = 0.9. \min\left(\sigma, \frac{IQR}{1.34}\right) . n^{\frac{-1}{5}}$$

Where: σ is the standard deviation, IQR is the interquartile range of the data, and n is the number of observations.

2.3. Data

The study used annual time series data from the WDI dataset provided by WB for the period 1987–2023 (36 observations), which met the condition that the number of observation years minus the number of variables was greater than 20, according to Tabachnick and Fidell (2013) and Manh, Nguyen, and Le (2022) . Three variables used in the study include: ecological footprint, which represents environmental quality; GDP per capita, reflecting the level of economic growth; and the proportion of industry in GDP, representing the level of industrialization. Table 1 presents the descriptive statistics of these variables, showing their mean, median, standard deviation, kurtosis, skewness, and range over the study period.

Table 1. Descriptive statistics of variables.

Indicator	EF (Global hectares per capita)	GDP (Per capita GDP, constant 2015 USD)	IND (Share of industrial value added, including construction, in GDP, %)
Mean	1.2862	1790.71	33.73
Median	1.1359	1609.96	35.39
Standard deviation	0.6085	948.69	5.00
Kurtosis	-1.1383	-0.85	-0.19
Skewness	0.4932	0.56	-0.94
Minimum value	0.5950	616.72	22.67
Maximum value	2.4323	3760.40	40.21
Number of observations	36	37	37

3. RESULTS AND DISCUSSION

3.1. Unit Root Test and Cointegration Test

The study employs two conventional approaches, the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) tests, to examine the stationarity of the time-series data. The results (Table 2) show that *lnGDP* is stationary at level [I(0)], while *lnEF* and *lnIND* become stationary after first differencing [I(1)]. Hence, all variables are integrated at either I(0) or I(1), satisfying the prerequisite conditions for applying the ARDL model in subsequent analysis. Table 2 presents the results of the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests.

Table 2. Results of unit root tests.

Null hypothesis (H_0): The variable has a unit root (non-stationary)

Variable	Model	ADF		PP		Order of integration
		At level	At first difference	At level	At first difference	
lnEF	Constant	0.5642^{ns}	-5.0171^{***}	0.6757^{ns}	-5.0389^{***}	I(1)
	Trend	-3.7906^{**}	-5.1390^{***}	-3.7475^{**}	-5.1910^{***}	
	None	-1.2715^{ns}	-1.1383^{ns}	0.4615^{ns}	-3.3689^{**}	
lnGDP	Constant	-3.7420^{***}	-3.1656^{**}	-0.7640^{ns}	-4.2488^{***}	I(0), I(1)
	Trend	-1.9446^{ns}	-5.5837^{***}	-1.5997^{ns}	-4.3615^{***}	
	None	19.8819^{ns}	-0.3102^{ns}	14.9934^{ns}	-0.4858^{ns}	
lnIND	Constant	-1.1079^{ns}	-5.5020^{***}	-1.1079^{ns}	-5.5020^{***}	I(1)
	Trend	-1.2946^{ns}	-5.6687^{***}	-1.4863^{ns}	-6.0129^{***}	
	None	0.7949^{ns}	-5.2640^{***}	0.7031^{ns}	-5.2581^{***}	

Note: *** and **, denote statistical significance at the 1% and 5% levels, respectively; "ns" indicates non-significance.
Unit root tests are conducted using the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) methods.

Table 3 shows that the F-statistic equals 6.3508, which exceeds the upper critical bound at the 1% level (I(1) = 5.61). Hence, the null hypothesis is rejected, confirming a long-run cointegrating relationship between EF and the variables GDP, GDP^2, and IND. This validates the use of the ARDL framework for subsequent analysis.

Table 3. Bounds test results for the ARDL model.

Null hypothesis (H_0): No cointegration exists

F-statistic	Critical values of the bounds test		
	Significance level	Lower bound – I(0)	Upper bound – I(1)
6.3508	10%	2.72	3.77
	5%	3.23	4.35
	1%	4.29	5.61

3.2. Short-Run and Long-Run Relationships

The previous Bounds Test results confirm the existence of a long-run cointegrating relationship between the ecological footprint (EF) and the variables GDP, GDP^2, and IND. The error-correction term (ECT) carries a negative sign (−0.6748) and is statistically significant at the 1% level, indicating a relatively fast adjustment speed toward long-run equilibrium following short-term shocks.

Table 4: ARDL model results.

Variable	Coefficient	Std. error	t-statistic	p-value
Short-run relationship				
EF (-1) *	-0.6390	0.1636	-3.9049	0.0008
GDP (-1)	1.4925	0.7075	2.1096	0.0471
GDP (-1) ^2	-0.0697	0.0429	-1.6252	0.1190
IND (-1)	-0.1600	0.1062	-1.5059	0.1470
D(GDP)	-2.9737	4.8676	-0.6109	0.5478
D (GDP (-1))	-3.6857	5.4725	-0.6735	0.5080
D(GDP (-2))	-15.3268	7.0301	-2.1802	0.0408
D(GDP^2)	0.2957	0.3313	0.8927	0.3822
D(GDP(-1)^2)	0.1817	0.3728	0.4874	0.6310
D(GDP(-2)^2)	1.0753	0.5006	2.1481	0.0435
D(IND)	-0.5161	0.1432	-3.6034	0.0017
C	-6.5126	2.6045	-2.5005	0.0208

Variable	Coefficient	Std. error	t-statistic	p-value
Short-run relationship				
Long-run relationship				
GDP(-1)	2.3357	0.9533	2.4502	0.0203
GDP(-1)^2	-0.1091	0.0635	-1.7173	0.0962
IND(-1)	-0.2503	0.1348	-1.8573	0.0731
	Model diagnostics			
Test	F-Statistic	p-Value		
Breusch–Godfrey serial correlation LM test	0.7651^{ns}	0.4791		
Breusch–Pagan–Godfrey heteroskedasticity test (Breusch-Pagan-Godfrey)	1.5102^{ns}	0.2005		

Note: D denotes the first difference, $D(Xt) = X_t - X_{t-1}$.

In the short run, GDP (-1) exerts a positive and statistically significant effect at the 5% level, indicating that short-term economic growth leads to an increase in the ecological footprint (EF). Several lagged differences of GDP^2 also show significant effects ($p = 0.0408$ and 0.0435), further reinforcing the nonlinear relationship. Notably, the first-difference industrial variable D(IND) has a negative and significant coefficient at the 5% level ($p = 0.0171$), suggesting that short-term industrial growth may be associated with environmental improvements, possibly due to technological adoption or structural transformation.

In the long run, GDP has a positive and statistically significant impact on EF, with an estimated coefficient of 2.3357, indicating that economic growth contributes to increasing environmental pollution. The GDP^2 variable has a negative coefficient (-0.1091) with a statistical significance of 10%, implying the existence of an inverted U-shaped nonlinear relationship, consistent with the EKC hypothesis. The IND variable has a negative coefficient (-0.2503) and reaches statistical significance at 10%, indicating that industrialization reduces environmental pollution in the long run.

The diagnostic tests in Table 2 and the results in Figure 1 show that the CUSUM and CUSUMSQ curves are both within the 5% confidence limit, indicating that the model does not have autocorrelation or heteroscedasticity problems, confirming the reliability of the estimation results.

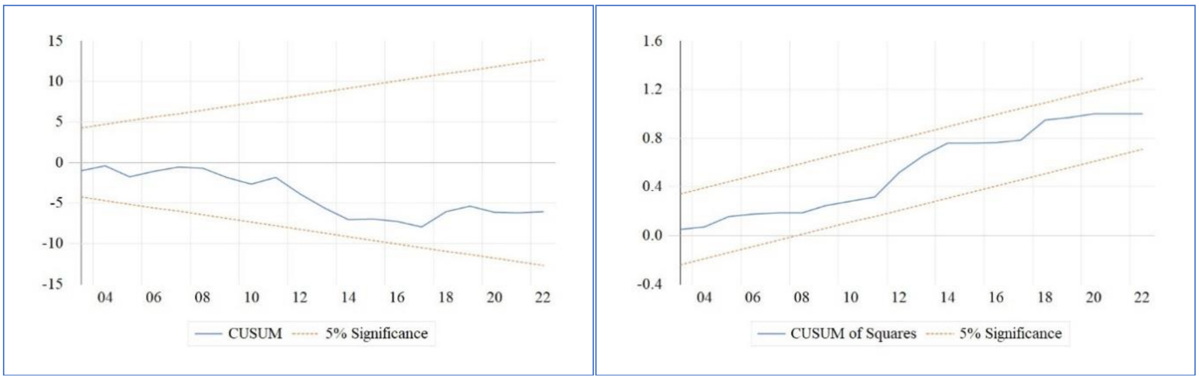

Figure 1. CUSUM and CUSUMSQ Plots of the ARDL Model.

3.3. Discussion

3.3.1. Economic Growth

During the period 1987–2023, Vietnam's GDP per capita and ecological footprint (EF) both increased over the years (Figure 2), reflecting the inverse relationship between economic growth and environmental quality. The estimation results from the ARDL model (Table 4) show that for every 1% increase in GDP per capita, the ecological footprint increases by about 2.34 ecological units, clearly reflecting that economic growth in Vietnam is accompanied by an increase in resource exploitation. The GDP^2 variable has a negative coefficient, indicating the existence of a nonlinear relationship according to the Environmental Kuznets Curve (EKC) hypothesis: in the initial stage, economic development causes environmental degradation, but after a certain GDP threshold, the ecosystem begins to improve.

Analysis using the QQR model (Figure 3) shows that the relationship between GDP and EF is not uniform across development levels. Specifically, at low quantiles of EF (τ from 0.05-0.25), the impact of GDP on EF is positive but at a low level. On the contrary, at medium to high quantiles (τ from 0.45-0.95), the impact of GDP on EF becomes strong; the coefficient $\beta(\tau, \theta)$ peaks around quantiles 0.65-0.85, indicating that when the economy surpasses the average level, GDP growth leads to a very clear increase in environmental pollution. This reinforces the argument that Vietnam is still on the left side of the EKC peak, i.e., has not reached the threshold where growth improves environmental quality. The consistency between the ARDL and QQR results confirms the nonlinearity in the GDP-EF relationship in Vietnam. This is an important result to propose differentiated policies according to the development stage: in the low GDP stage, it is necessary to control emissions from the beginning, and in the higher GDP stage, it is necessary to promote clean technology and renewable energy to quickly move to the right of the Kuznets curve.

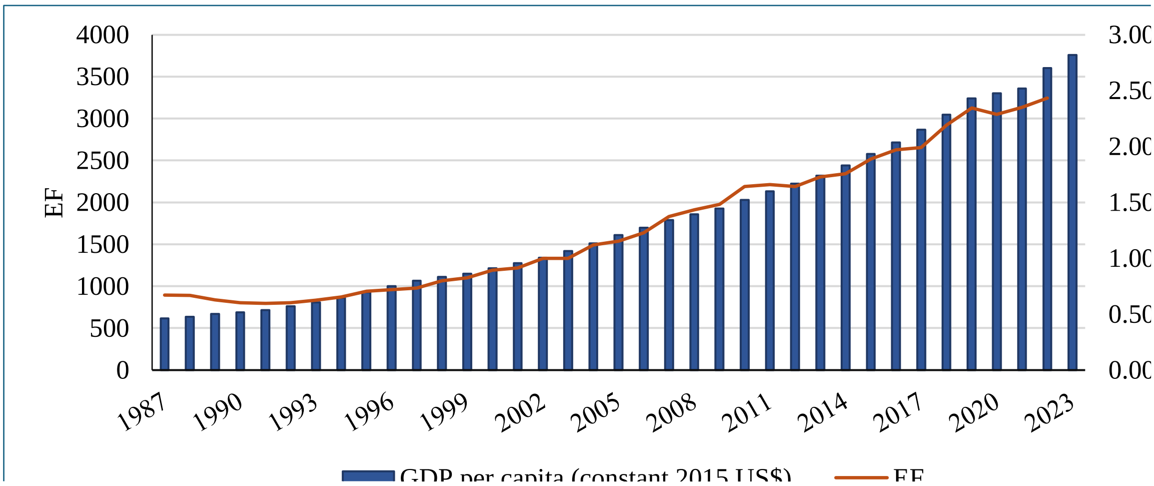

Figure 2. Ecological Footprint and Per Capita GDP in Vietnam, 1987–2023.

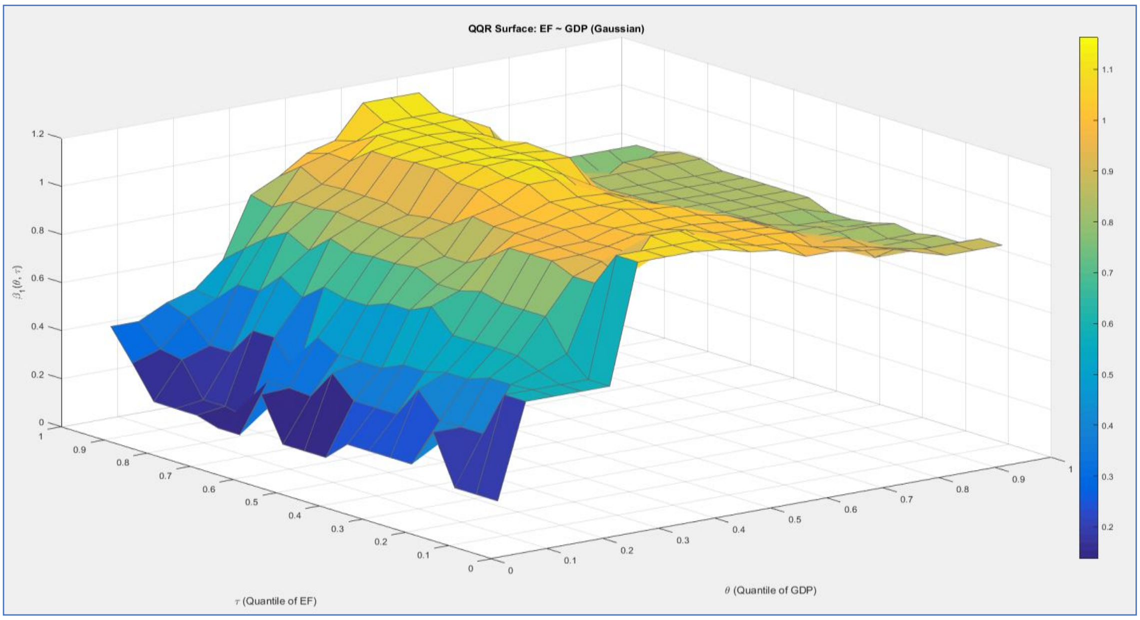

Figure 3. Quantile-on-Quantile Relationship between GDP and Ecological Footprint in Vietnam (1987–2023).

Compared with previous studies, the results are consistent with Bui, Nguyen, and Bui (2023) who tested the EKC with CO_2 data and found a nonlinear relationship between economic growth and environmental quality. However, this study's results are contrary to the study of Bui et al. (2023) which found that GDP contributed to reducing N_2O emissions, but showed that GDP is still a factor increasing the ecological footprint in Vietnam. In addition, the results of this study are also contrary to the findings of Nguyen et al. (2022) that GDP has a proportional effect on greenhouse gas emissions, with no signs of reversing the trend of EKC. Overall, the results of this study confirm that the development process in Vietnam has not yet reached a clear stage of environmental improvement, but signs of bending have begun to appear, especially at the high percentiles of GDP. This shows the potential for adjusting industrial production and energy use policies to promote growth while minimizing environmental pollution.

3.3.2. Industrial Production

During the period 1987–2023, industrial production (IND) and ecological footprint (EF) in Vietnam both increased significantly (Figure 4). The results from the ARDL model (Table 4) show that the IND variable has a negative coefficient in the long run, which indicates that, in the long-term trend, industrialization in Vietnam has the potential to improve environmental quality (reduce ecological footprint), especially when this process is accompanied by improvements in energy efficiency.

However, the results from the quartile-to-quartile regression (QQR) (Figure 5) show that the relationship between IND and EF is nonlinear and heterogeneous. Specifically, at low quantiles of EF (from 0.05 - 0.30), the impact of IND is significantly negative, reflecting that in the context of low environmental pollution, industrialization can support environmental improvement through technological innovation and production process optimization. In contrast, as EF increases to the middle and high quantiles (τ from 0.45 and above), the coefficient $\beta(\tau,\theta)$ gradually shifts to positive, even exceeding the threshold of $\beta > 0$ at high quantiles, indicating that in periods of high environmental pollution, increased industrial production also increases ecosystem degradation. The QQR regression surface confirms this transition, with $\beta(\tau,\theta)$ fluctuating from negative to positive significantly with the increase of EF and IND. This result emphasizes the nonlinear relationship between industrial production and the environment in Vietnam.

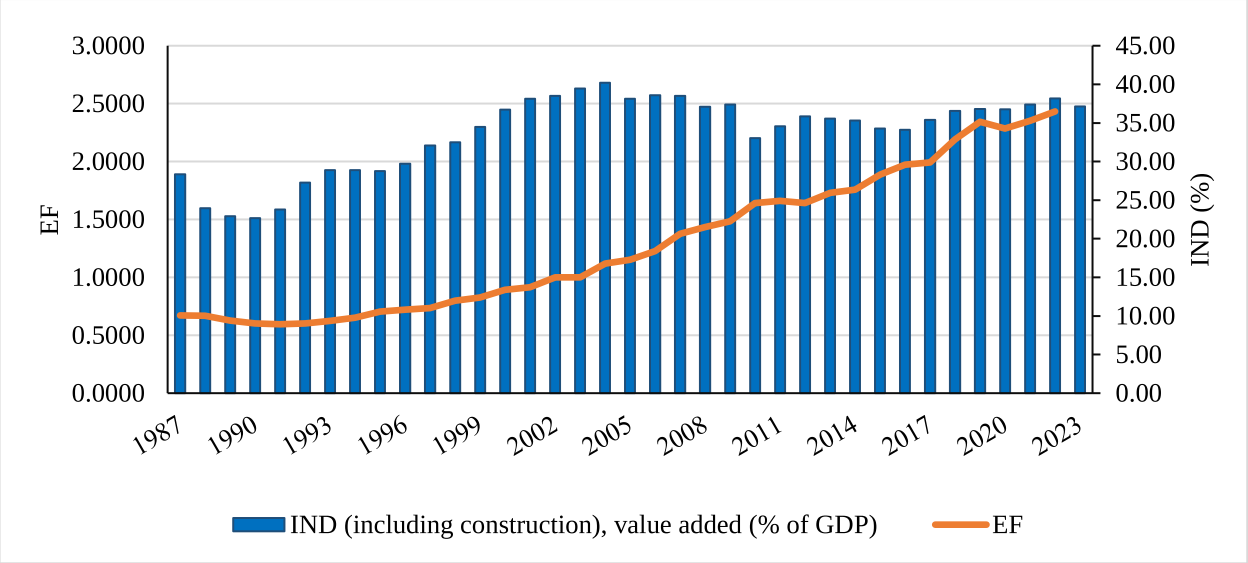

Figure 4. Industrial Production Value and Ecological Footprint in Vietnam, 1987–2023.

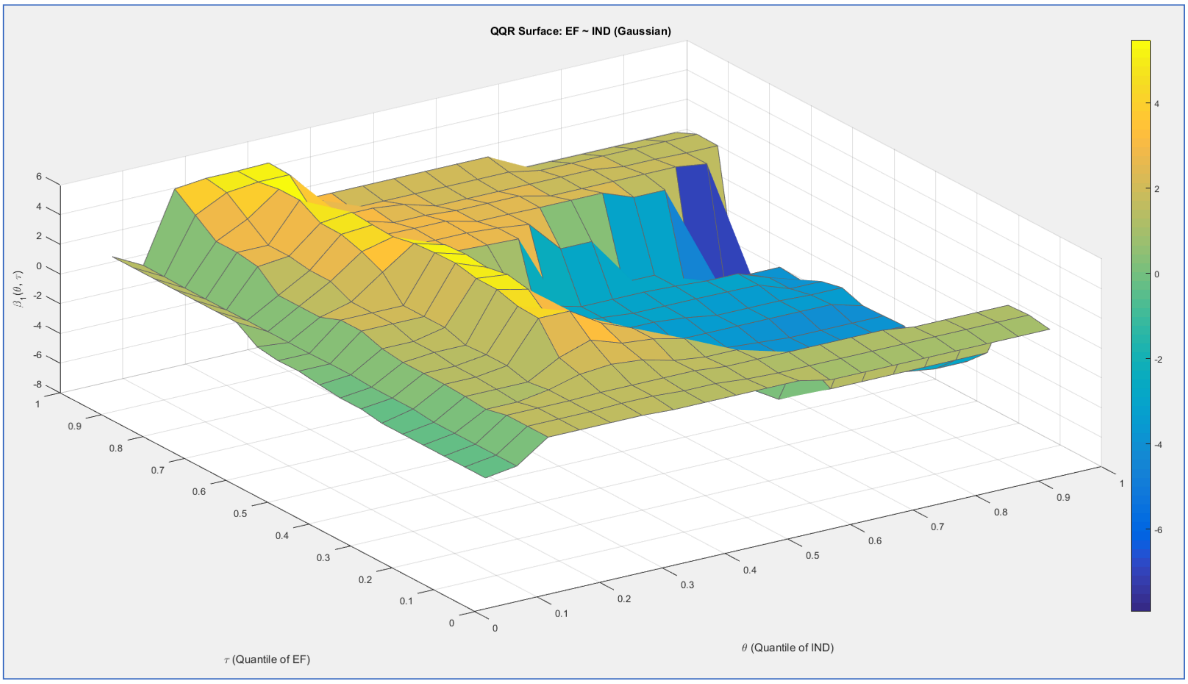

Figure 5. Quantile-on-Quantile Relationship between Industrial Production and Ecological Footprint in Vietnam, 1987–2023.

Compared with previous studies, this study's results are consistent with Son (2024). The author argues that industrialization in Vietnam, thanks to technological innovation and export orientation, has helped reduce emissions in the early stages. However, it is contrary to the results of Hassan, Siddique, Sumaira, and Alvi (2025) and Sikder et al. (2022) showing that industrialization increases pollution in South Asia and many developing countries. In addition, the finding of Su, Wang, Li, and Wang (2022) on the "improvement threshold" in the industrialization process, that is, after passing a certain level of environmental pollution, the impact can become positive, which is completely consistent with the QQR model in this study. Overall, the research results have shown that in the stage of low environmental pollution, it is necessary to take advantage of the opportunity to promote green industrialization; as pollution increases, stricter environmental control policies are needed for the industrial sector to avoid increasing its ecological footprint.

Thus, the results from the ARDL and QQR models show that the relationship between economic growth, industrial production, and ecological footprint in Vietnam is a non-linear relationship. GDP growth increases the ecological footprint, but signs of bending along the environmental Kuznets curve have begun to appear at high income levels. High levels of industrial production have become a factor causing environmental pollution. These findings require industrial policy and environmental protection according to each stage of industrial development.

4. CONCLUSION AND POLICY IMPLICATIONS

This study examined the relationship between ecological footprint (representing environmental quality) and economic growth, industrial production in Vietnam from 1987 to 2023, using a combination of the ARDL model and QQR regression. The results showed that GDP has a positive impact on ecological footprint in the long run, and there is a non-linearity consistent with the environmental Kuznets curve hypothesis. Industrial production increases environmental pollution as industrial production increases. These findings affirm the importance of building flexible economic and environmental protection policies suitable for each stage of economic and industrial development.

Based on the empirical results, several policy implications are proposed.

On that basis, the study proposes a number of policy implications.

First, it is necessary to continue promoting the implementation of the National Green Growth Strategy for the period 2021–2030 (Decision 1658/QD-TTg) and commitments to the target of net zero emissions by 2050, while integrating environmental goals into the national industrial development strategy. The development of eco-industrial parks according to Decree 35/2022/ND-CP also needs to be prioritized, along with mandatory requirements for automatic monitoring systems and public disclosure of environmental data in key industrial parks to enhance transparency and effective monitoring.

In addition, attracting foreign investment requires applying an FDI screening mechanism based on environmental, social, and ESG governance criteria, according to the Law on Environmental Protection 2020 and Decree 08/2022/ND-CP detailing a number of articles of the Law on Environmental Protection, to ensure that FDI capital flows contribute to improving environmental quality and promoting clean technology transfer. At the same time, it is necessary to accelerate the establishment and operation of the domestic carbon market according to Decision 01/QD-TTg in 2022 on implementing greenhouse gas inventories, in order to form an economic mechanism to encourage enterprises to reduce emissions in energy-intensive industries.

Finally, environmental policies need to be flexibly adjusted according to each stage of economic development. When income reaches a higher level, the focus should shift to innovation, renewable energy development, and the circular economy. These orientations need to be linked to the implementation of Resolution 57-NQ/TW in 2024 on breakthroughs in science, technology, innovation, and national digital transformation, in order to support Vietnam in rapidly shifting to a greener, more ecologically efficient, and sustainable development phase.

The above implications not only support the implementation of Vietnam's sustainable growth goals but also make practical contributions to international commitments on climate change and global green development.

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