

Exploring the key factors between economic growth and environmental degradation: the Kuznets Curve in the Ecuadorian context

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Abstract

Aim: The objective of this work was to evaluate the applicability of the Environmental Kuznets Curve (EKC) in the Ecuadorian context.

Methodology: An econometric analysis was carried out using the ARDL model to assess its validity in the Ecuadorian context, identifying significant relationships between economic growth and environmental degradation in the short and long term. This approach made it possible to examine the temporal dynamics between variables, revealing possible causal effects and providing an empirical basis for sustainable policymaking.

Results: The results indicate that Ecuador exhibits a nonlinear long-term relationship between economic growth and CO₂ emissions consistent with the Environmental Kuznets Curve. In the long run, economic growth and energy consumption are significant determinants of environmental degradation, while institutional quality does not play a structural role. In the short run, emissions dynamics are driven mainly by changes in energy consumption and institutional conditions, highlighting the importance of energy dependence and governance factors in shaping environmental outcomes.

Implications and recommendations: This study highlighted the need to adopt comprehensive strategies that foster sustainable growth by transitioning to renewable energy sources, implementing cleaner technologies, and strengthening environmental legislation.

Originality/value: The relationship between economic growth and environmental degradation has been extensively studied using the Environmental Kuznets Curve (EKC), however this article focused specifically on Ecuador, which constitutes an original contribution by applying a dynamic ARDL model with national data. The study provided novel empirical evidence in a country characterised by its high environmental diversity and structural challenges, demonstrating that, even within Latin America, Ecuador presents unique patterns that warrant a specific analysis.

Keywords: Environmental Kuznets Curve (EKC), CO₂ emissions, environmental degradation, economic growth, autoregressive distributed lag

1. Introduction

In recent decades the link between economic growth and environmental sustainability has become a central issue on the global research agenda, driven by growing concern about ecological deterioration (Chakravarty & Mandal, 2020; Aziz et al., 2020). Within this regional panorama, Ecuador stands out as a relevant example due to its high levels of greenhouse gas (GHG) emissions, the accelerated pace of urbanization, the expansion of the agricultural frontier, and the strong dependence on fossil fuels (Hussain et al., 2023). One of the most widely used theoretical frameworks to analyse this relationship between economy and environment is the Environmental Kuznets Curve (EKC) (Awan & Azam, 2022; Aquilas et al., 2022), stating that the environmental impact tends to worsen in the early phases of economic development, but improves once a certain level of income is reached, resulting in an inverted U-shaped relationship (Gu & Zheng, 2021; Koondhar et al., 2021).

Recently, Ecuador's economic dynamism has intensified the use of natural resources, especially through activities such as mining, oil exploitation, and agribusiness, which have been key drivers of deforestation, biodiversity loss, and pollution (ClimateWatch, 2020). These phenomena are aligned with patterns observed at regional level in Latin America (Aslam et al., 2021; Freire et al., 2023), therefore it is essential to identify the economic and social determinants that shape this relationship, in order to better understand the conditions under which it is possible to reconcile economic development and environmental sustainability (Ahmad et al., 2021; Jeetoo & Chinyanga, 2023).

This study aimed to evaluate the applicability of the Environmental Kuznets Curve (EKC) in the Ecuadorian context, in order to understand how this relationship has evolved over time and what

determining factors influence the interaction between economic growth and environmental degradation. Based on the following key questions – What changes have occurred in the evolution of the EKC in Ecuador? What factors determine the relationship between economic growth and environmental degradation in the Ecuadorian context of the Kuznets Environmental Curve? – an analysis was proposed to provide empirical and conceptual evidence on the environmental dynamics of the country.

2. Literature review

2.1. The Environmental Kuznets Curve: the relationship between economic growth and environmental degradation

The Environmental Kuznets Curve (EKC) hypothesis points to a dynamic relationship between economic growth and certain indicators of environmental degradation, such as polluting emissions. This idea, initially developed by Grossman and Krueger (1991), suggests that, in the early stages of economic development, an increase in per capita income is associated with increasing environmental deterioration. However, once a certain threshold of income is reached, the trend reverses and environmental quality begins to improve. This relationship takes the form of an inverted U curve.

The theoretical foundation of the EKC is inspired by the traditional Kuznets Curve (Kuznets (1955)), suggesting a similar relationship between economic development and income inequality. Similarly, in the environmental version, it was observed that both social inequality and environmental degradation tend to increase in the early phases of growth, but decrease later as economic development improves (Bibi & Jamil, 2020). In this sense, the EKC hypothesis has been widely discussed and supported by various studies. Jeetoo & Chinyanga (2023) pointed out that the relationship between economic growth and environmental degradation is non-linear, and that this model remains useful for understanding how economic activity can affect – and eventually improve – the natural environment. Satici and Cakir (2021) highlighted the importance of the numerous empirical studies that confirm the existence of this relationship in different contexts, which reinforces the validity of the model.

On the other hand, more recent research e.g. that by Dinda et al. (2021) and Lee and Thiel (2017) provided additional empirical evidence that supports the applicability of EKC in several countries. Hao et al. (2021) stated that, upon reaching a certain level of income, environmental improvements can be attributed to greater ecological awareness, stricter regulations, and the use of clean technologies. Subsequent studies, such as those by Dasgupta et al. (2006), Kaika and Zervas (2013), Khan et al. (2022), and Nasir and Rehman (2023), continued to strengthen the validity of this theory. For example, Le et al. (2020) analysed deforestation as an environmental indicator, while Shojaie and Fox (2022) used variables such as industrial emissions, wastewater discharges, and solid waste generation to assess the validity of the EKC model.

However, not all studies agree on the exact form of this relationship, and some authors have identified more complex patterns. For example, Wang et al. (2014), in their analysis of the Chinese province of Zhejiang, observed that the EKC initially presented an inverted U shape, but later evolved into a wavy pattern, reflecting temporal and spatial variations. Moreover, Sinha, Shahbaz and Balsalobre (2017) proposed an N-shaped relationship between income and carbon emissions, suggesting the existence of two tipping points throughout the development process.

In Latin America the empirical validity of EKC has been explored through econometric approaches that combine cointegration techniques, ARDL models and variants such as UECM, VECM and structural rupture analysis. These studies have incorporated variables such as GDP, CO₂ emissions, economic complexity, the degree of globalisation and the composition of the energy matrix, also considering the structural particularities of each country. Table 1 summarises recent research showing that KD manifests itself heterogeneously in the region, with strong evidence in some cases, partial results in others, and the absence of a clear relationship in certain contexts.

Table 1. Recent studies on EKC in Latin American countries

Author	Country(s)	Methodology	Key variables	EKC Form
Acevedo-Ramos et al., (2023)	Colombia	ARDL bounds + UECM	CO ₂ per capita, GDP, Economic Complexity	U-inverted in the long term
Okere et al., (2022)	Peru	ARDL + cointegration	CO ₂ per capita, GDP per capita, globalisation, financial development, fossil fuels	U-inverted with medium inflection point
Seri & Fernández (2021)	21 LAC countries	ARDL bounds + UECM	CO ₂ per capita, GDP per capita + controls (urbanisation, FDI, etc.)	EKC valid only in a few countries
Hwang, (2023)	Argentina, Brazil and Chile	ARDL + VECM	CO ₂ emissions, GDP, energy (oil, gas, hydro, renewables)	Partial EKC; Clean Energy Improvements
Raihan et al., (2025)	Mexico	ARDL + structural ruptures	CO ₂ , GDP, renewable energy, FDI, globalisation	Inverted U (policy-modulated effect)

Source: own elaboration.

These studies show considerable heterogeneity in the results on the existence and form of the EKC in Latin America. For example, in Colombia and Mexico evidence was found of an inverted U-shaped relationship between economic growth and CO₂ emissions in the long term, suggesting that, after a certain threshold of entry, environmental degradation decreases (Acevedo-Ramos et al., 2023; Raihan et al., 2025). In Peru EKC was also partially validated, although the turning point was located at a medium income level (Okere et al., 2022). In contrast, studies covering multiple Latin American countries showed that EKC was not uniformly verified, but depends on specific factors such as the type of energy used, foreign direct investment, and the degree of urbanisation (Seri & de Juan Fernández, 2021; Hwang, 2023). This diversity of findings reinforces the need to conduct contextualised and technically sound analyses in each country, using methodologies such as the ARDL model to adequately capture the dynamic relationships between economic and environmental variables.

2.2. Factors that affect the relationship between economic growth and environmental quality

The relationship between economic growth and environmental quality has been widely debated in the economic and environmental literature, due to its complexity and the multiplicity of variables involved. Bibi and Jamil (2020) proposed an analytical framework based on three key factors: the scale effect, the composition effect, and the technical effect. The first, the scale effect, refers to the increase in economic activity and its correlation in the intensive use of natural resources and the generation of polluting emissions, which exerts direct pressure on ecosystems (Dinda, 2021). In this sense, environmental management is decisive in mitigating these impacts (Lemkowska & Wiśniewska, 2021). Lee and Thiel (2017) stressed that, as the economy grows, energy consumption and industrial production increase, which raises pollution levels if adequate regulatory measures are not implemented. Romanowska et al. (2021) agreed that the initial stages of economic development are often marked by increased environmental pressure due to limited regulatory enforcement and low adoption of clean technologies.

The second component, the composition effect, refers to the productive structure of an economy and its impact on the environment. According to Zhang (2012), economies with a predominance of service or agricultural sectors tend to generate fewer negative impacts than those based on heavy industry or intensive manufacturing. According to Aquilas et al. (2024), industrialisation has substantial adverse effects on environmental quality, underscoring the importance of sustainable development strategies. Haseeb et al. (2019) argued that a productive reorientation towards less carbon-intensive sectors, accompanied by effective public policies, can substantially improve environmental conditions. The third element, the technical effect, is related to advances in technology and production efficiency that allow more goods and services to be produced using fewer resources and generating lower polluting emissions (Aldieri, 2021). This effect implies that, as an economy progresses, innovation, the adoption of clean energy, and the improvement of industrial processes can offset or reverse the negative impacts of economic growth (Grossman & Krueger, 1995).

According to Dong et al., (2021), investment in research and development, as well as the transfer of clean technologies, can accelerate the transition to a low-emission economy. In addition, Haseeb et al. (2019) suggested that international cooperation and openness to trade can facilitate the diffusion of these innovations, reducing carbon intensity even in economies with high industrial activity. Although Bibi's and Jamil's (2020) scheme is recurrent in empirical studies, it is not the only theoretical approach. Dinda et al. (2021) and Seri & de Juan Fernández (2023) integrated additional dimensions such as the role of technological innovation, trade openness, and environmental governance, as they can significantly alter the relationship between economy and environment. Rosado-Anastacio (2018) argued that institutional efficiency and international cooperation are critical variables for reducing environmental pressure, even in contexts of accelerated growth.

These divergences show that although the three-effect model is widely cited, there is an open debate regarding the weighting of each factor and the incorporation of other explanatory elements (cf. Dong et al. (2021)). Overall, this diversity of approaches reflects the fact that the relationship between economic growth and environmental quality cannot be understood in a linear or single way. Rather, it responds to a web of interdependent factors that include not only scale, composition, and technology, but also institutional, political, and social elements, reinforcing the need for a contextualized analysis for each economy.

3. Methodology

This study adopted a comprehensive econometric approach, focusing on a dynamic analysis to evaluate the applicability and validity of EKC in the Ecuadorian context. This approach is based on the complementary model, namely the ARDL Limit Test with a causality analysis that was used to prove cointegration in the long term. Through this method, it is expected that one can identify the short and long-term relationships between economic and environmental variables.

The selection of lags was made using the Akaike Information Criterion (AIC), prioritising the lowest possible value, which allows a balance between model fit and parsimony (Kasali & Adeyemi, 2022). Up to four lags were considered due to the availability of data and to avoid the loss of degrees of freedom. The final choice, ARDL (1,0,2,2,2), reflected the ability of the included lags to capture the temporal inertia and dynamic relationships between the variables.

3.1. ARDL Limits Test of Cointegration ARDL Model (Autoregressive Distributed Lag Model)

According to the EKC hypothesis, higher economic growth will lead to a certain level from which it will generate a reduction in environmental degradation. This hypothesis was tested by applying the Autoregressive Distributed Lags (ARDL) model that allows establishing the relationship between carbon dioxide (CO₂) emissions, Gross Domestic Product (GDP) per capita, Energy Consumption and Corruption Perception Index (see Table 2).

Table 2. Description of variables

Variable Type	Variable	Description	Unit of Measure	Expected Sign
Endogenous	CO ₂ emissions	Amount of carbon dioxide emissions per inhabitant at country level.	Metric tons per capita	N/A
Exogenous	GDP per capita	Gross Domestic Product per capita per capita at country level.	Constant Dollars (USD)	(+)
	GDP per capita squared	GDP per capita squared, capturing nonlinear effects at country level.	Constant Dollars (USD ²)	(-)
	Energy consumption per capita	Energy consumption per capita of energy per capita at country level.	Kilowatt hours (kWh)	(-)
	Corruption Perceptions Index	The perceived level of corruption in the public sector is measured on a scale where higher values indicate less corruption.	Index (0 to 100)	(-)

Source: own elaboration.

The ARDL cointegration approach allows estimating long-term relationships efficiently, regardless of the order of integration of the variables. This model is especially suitable for analysing both short and long-term dynamics in time series, even when the variables have different orders of integration, either I(0) or I(1) (Zambrano-Monserrate et al., 2016). The functional specification of the ARDL-ECM model (equation 1) which captures the short-run dynamics of the variables is:

$$\begin{aligned} \ln(CO_2)_t = & \delta_0 + \sum_{i=1}^P \delta_1 \ln(GDP)_{t-i} + \sum_{j=0}^{q_1} \delta_2 \ln(GDP)_{t-j}^2 + \sum_{k=0}^{q_2} \delta_3 \ln(E)_{t-k} \\ & + \sum_{l=0}^{q_3} \delta_4 \ln(IPC)_{t-l} + \theta ECT_{t-1} + \varepsilon_t, \end{aligned} \quad (1)$$

where

$\ln(CO_2)$ – natural logarithm of carbon dioxide emissions,

$\ln(GDP)$ – natural logarithm of GDP per capita,

$\ln(GDP)^2$ – GDP per capita squared logarithm, which allows us to capture nonlinear effects such as the inverted U-shape of the Kuznets Environmental Curve,

$\ln(E)$ – natural logarithm of energy consumption per capita,

$\ln(IPC)$ – natural logarithm of the Corruption Perceptions Index,

δ – short-term effects,

ε – stochastic error term,

ECT_{t-1} – lagged error correction term, residuals of the long-run regression.

This model allowed to evaluate whether there was empirical evidence that supports the hypothesis of the Environmental Kuznets Curve in Ecuador, identifying both short and long-term relationships between economic growth and environmental degradation. The inclusion of the quadratic term of GDP per capita enabled to analyse whether CO₂ emissions initially increase with economic growth and then decrease when they reach a critical level of development (Awan et al., 2022).

3.2. Causation analysis

In time series analysis, causality can be assessed using a vector autoregressive (VAR) model or a vector error correction model (VECM). For VAR, the Toda-Yamamoto approach to Granger causality testing was applied, which allows for the evaluation of causal relationships even when the series are integrated or cointegrated (Toda & Yamamoto, 1995). This procedure, also called augmented VAR, is a robust methodology in the face of different integration orders and the existence of cointegration between variables (Abbasi & Riaz, 2016).

4. Results

This section presents an overview of the findings obtained in the study, with the purpose of offering a clear overview of the economic and environmental evolution of the country. The analysis was organised in such a way as to understand how the main variables behaved over time and what significant patterns or changes could be identified. Figure 1 presents the trajectory of Ecuador's Gross Domestic Product (GDP) during the period analysed in order to contextualise the economic dynamics and its possible relationship with the EKC hypothesis. This visual representation made it possible to identify cyclical behaviour and abrupt changes that could be linked to external and internal factors of the economy, as well as to assess the stability of growth over time (Ahmad et al., 2021).

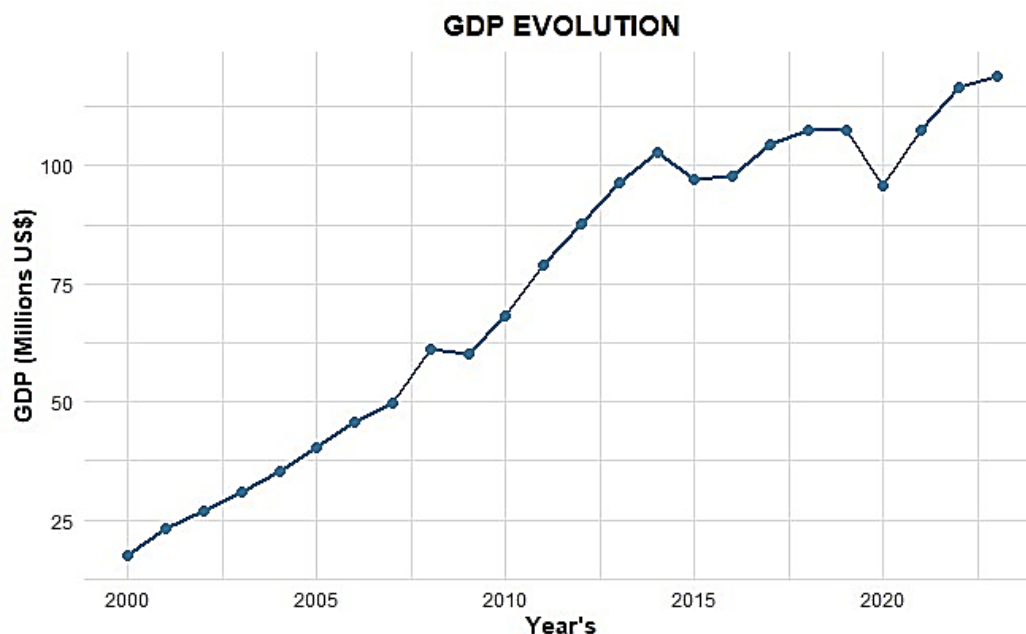


Fig. 1. Evolution of the Gross Domestic Product (GDP)

Note: The graph illustrates the annual changes in total GDP, highlighting episodes of sustained growth and periods of slowdown that can be associated with structural changes and economic conjunctures. Data expressed in millions of current USD.

Source: World Bank (2025).

The above shows a general growth trend interrupted by episodes of slowdown and recovery. Peaks are observed that coincide with phases of sustained economic expansion, followed by declines that reflect periods of contraction or adjustment. These movements suggest the influence of external shocks, variations in export prices, and adjustments in economic policy, which reinforces the need to analyse not only the level of production, but also the sectoral composition that sustains it.

4.1. Diagnostic tests

An assumption of the ARDL methodology is that variables should be stationary up to order 1, or level (Menegaki, 2019). In order to verify the stationarity of the variables and, therefore, avoid spurious regression, all model variables were subjected to the unit root test before estimation (Llerena Guevara et al., 2024). Two unit root tests with a significance level of 5% were carried out: the augmented Dickey-Fuller test (ADF) and the Phillips Perron test in order to determine the stationarity of the model variables. These tests allowed to identify whether the variables were stationary in level or required a first differentiation to achieve this condition. The decision-making in this analysis was based on the following hypothesis:

- Ho: The series has a Unit Root (The series is not Stationary). > 0.05 ,
- H1: The series does not have a Unit root (The series is Stationary). < 0.05 .

The results of the Dickey-Fuller test indicated that the natural logarithm of CO₂ emissions, the natural logarithm of energy consumption, the natural logarithm of GDP, the natural logarithm of GDP squared, and the natural logarithm of the corruption perception index are all stationary in first differences. This implies that each variable is integrated of order one, $I(1)$. The results presented in Table 3 confirmed that the stationarity condition required for the econometric analysis was satisfied, allowing the model to be estimated without the risk of spurious regression.

Table 3. Dickey-Fuller Unit Root Testing

Variable	Dickey-Fuller at level	Dickey-Fuller at first difference
lnCO ₂	0.2563	0.0009
lnGDP	0.8432	0.0052
lnGDP ²	0.2282	0.0447
lnE	0.9490	0.0010
lnIPC	0.2716	0.0172

Source: own elaboration.

The results obtained from the Phillips-Perron test were consistent with those of the augmented Dickey-Fuller test, with only minor differences in the test statistics (see Table 4). However, in terms of stationarity, both tests led to the same conclusion, confirming that all logarithmic variables are stationary in first differences. This consistency across tests reinforces the robustness of the results and supports the validity of the stationarity diagnostics conducted prior to the econometric analysis.

Table 4. Phillips Perron Unit Root Tests

Variable	Phillips-Perron at the level	Phillips Perron at first difference
lnCO ₂	0.3059	0.0002
lnGDP	0.8613	0.0031
lnGDP ²	0.1240	0.0447
lnE	0.9598	0.0008
lnIPC	0.2247	0.0172

Source: own elaboration.

Once the stationarity tests had been carried out, it was necessary to reformulate the proposed model based on the results obtained. This adjustment allowed to guarantee the validity of the analysis and a better interpretation of the effects of the variables. Depending on the nature of the data, the variables were expressed in the first difference or at level, thus ensuring that the model correctly reflects the relationships between them. With this new specification, it was possible to evaluate the impact of each variable more rigorously and obtain more precise conclusions about its behaviour over time, according to which the model could be structured as follows:

$$\Delta \ln(CO_2)_t = \delta_0 + \sum_{i=1}^P \delta_1 \Delta \ln(GDP)_{t-i} + \sum_{j=0}^{q_1} \delta_2 \Delta \ln(GDP)_{t-j}^2 + \sum_{k=0}^{q_2} \delta_3 \Delta \ln(E)_{t-k} + \sum_{l=0}^{q_3} \delta_4 \Delta \ln(IPC)_{t-l} + \theta ECT_{t-1} + \varepsilon_t, \quad (2)$$

where Δ represents the first difference.

Once the unit root tests were carried out and the stationarity conditions of the variables verified, the ARDL (AutoRegressive Distributed Lag) model was estimated to analyse the short and long-term relationships between the variables (Galadima et al., 2022). Next, additional diagnostic tests were applied in order to evaluate the suitability of the model and the validity of the estimators. In particular, the Breusch–Godfrey tests were used for autocorrelation, Breusch–Pagan for heteroskedasticity, Jarque–Bera for residue normality and Ramsey RESET for the correct functional specification. The results showed no evidence of autocorrelation (Breusch–Godfrey LM test, $p = 0.4600$), heteroskedasticity (Breusch–Pagan test, $p = 0.3014$), significant departures from normality (Jarque–Bera test, $p = 0.5338$), or model misspecification (Ramsey RESET test, $p = 0.4951$). Overall, these diagnostic tests support the statistical robustness and adequacy of the estimated ARDL model.

Table 5. Model Diagnostic Tests

Test	Result
Breusch–Godfrey (LM)	0.4600
Breusch–Pagan	0.3014
Jarque–Bera	0.5338
Ramsey RESET	0.4951

Source: own elaboration.

Figure 2 provides a visual representation of the behaviour of the variables by means of Q-Q (quantile-quantile) graphs, allowing to evaluate whether the data follow a normal distribution. This test, although informal, can serve as a key criterion for determining the EKC trajectory. The ascending shape of all distributions suggests that there was an increasing pattern in the analysed data, consistent with the EKC hypothesis. This economic theory, proposed by Kuznets (1955), postulates that in the early stages of economic growth environmental degradation increases until it reaches a tipping point, after which the relationship is reversed and environmental quality improves as economies develop and adopt cleaner technologies.

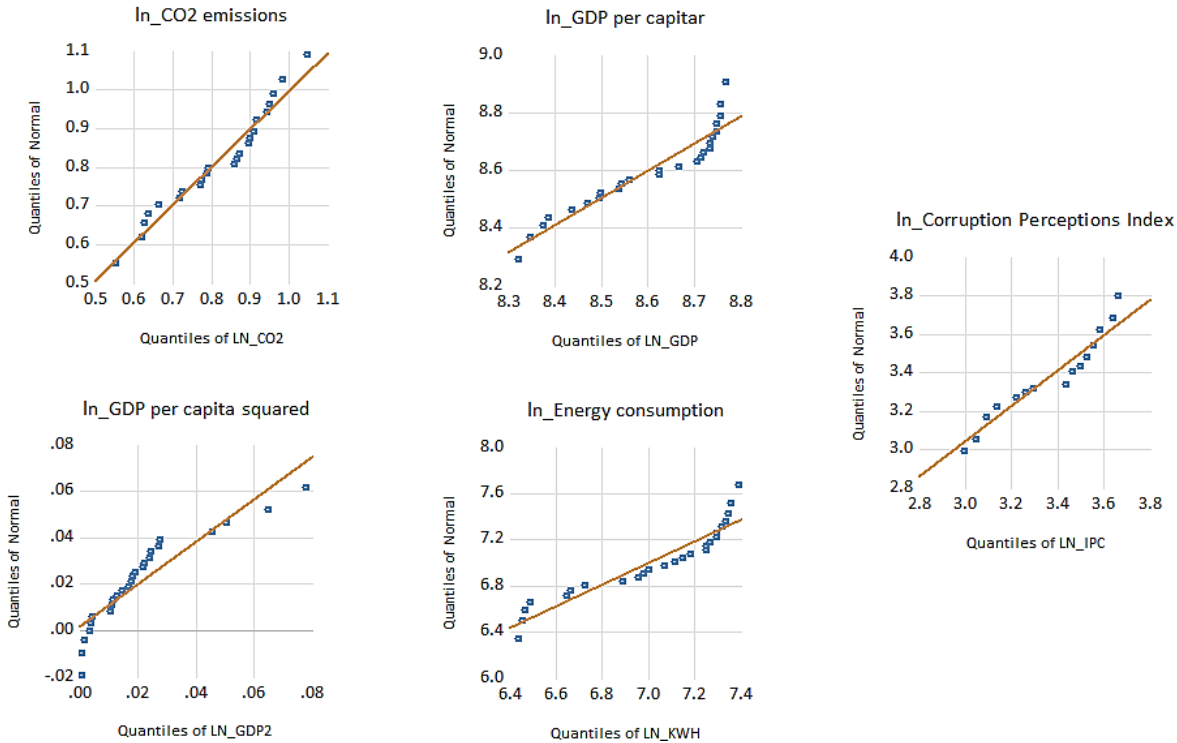


Fig. 2. Behaviour of the variables

Source: own elaboration.

From this perspective, the trend observed in the graphs could indicate a phase of economic growth in which emissions and other environmental impacts were still on the rise, yet to validate this criterion conclusively, more rigorous econometric testing would be required. However, this preliminary analysis is useful for guiding hypotheses and assessing whether the data follow a pattern consistent with the EKC. In this sense, studies such as those by Grossman and Krueger (1991) pointed out that the relationship between growth and environmental degradation is not linear, but depends on factors such as environmental policies, technological innovation and economic structure.

Figure 3 shows the relationship between the logarithm of GDP per capita and the logarithm of CO₂ emissions per capita for Ecuador during the period 2000–2024. The quadratic adjustment line (in red) has a positive slope, indicating that throughout the period studied, higher levels of economic activity

were associated with increased CO₂ emissions. This suggests that Ecuador remains in the ascending phase of the EKC, where economic growth intensifies environmental pressure.

The linear trend (in blue) shows a slight reduction in slope at higher income levels, however no clear turning point was observed that would indicate the beginning of the downward phase of the curve. In other words, the structural transformation required to decouple economic growth from environmental degradation had not yet occurred. These results are consistent with the theory proposed by Grossman and Krueger (1991), stating that in the early stages of development, increases in per capita income tend to be accompanied by higher levels of pollution before technological, institutional, and productive changes reverse this trend.

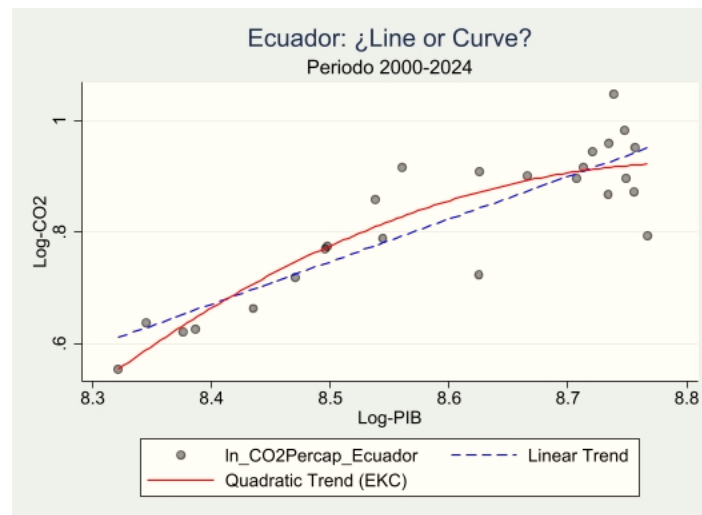


Fig. 3. EKC for Ecuador

Note: This graph represents the initial phase of the EKC scenario, where economic growth is still associated with an increase in CO₂ emissions. The turning point and subsequent decline expected by the theory were not observed.

Source: own elaboration.

4.2. Results of the ARDL model

The ARDL method was used because it has better properties for small samples (Narayan & Narayan, 2005). The article presents estimates for the long and short term in order to identify the dynamic relationships between economic growth, pollutant emissions and control variables linked to the EKC hypothesis. This approach enabled to distinguish the immediate effects of variations in GDP and other determinants on the level of emissions from the equilibrium effects manifested over time, providing evidence on the validity or not of EKC in the context analysed.

Before interpreting the results of the model specification diagnostic, the statistical hypotheses underlying the applied test were formally stated. These hypotheses allow for the assessment of whether the functional form of the model is appropriate, or whether specification errors arise from omitted relevant variables or an incorrect econometric formulation.

- **(H₀):** The model is correctly specified (there are no specification errors).
- **(H₁):** The model has specification errors (incorrect functional form or omission of relevant variables).

From the Table 6 specification diagnosis, it can be observed that variables hat and hatsq, which correspond to the fitted values and their squares, had p-values of 0.868 and 0.360, respectively. These values were clearly higher than the conventional significance level of 5%. Consequently, the null hypothesis was not rejected, indicating that there was no statistical evidence of specification errors in the model. This suggests that the applied functional form was appropriate and that no relevant

omission of explanatory variables was detected. Additionally, the adjusted R-squared value and the joint non-significance of the added terms reinforced the conclusion that the model was correctly formulated from an econometric specification standpoint. The table reports the results of the link test for model specification. The test evaluated potential misspecification by examining the significance of the fitted values (\hat{y}) and their squared term (\hat{y}^2). A non-significant coefficient on \hat{y}^2 showed that the model was correctly specified and that no relevant variables were omitted.

Table 6. Specification diagnosis

ln_CO ₂	Std. err.	P> t
hat	0.862738	0.868
hatsq	24.1781	0.360
Cons	0.014924	0.365
Adj R-squared	2.518870	0.8353

Source: own elaboration.

In Table 7 the error correction term (ECT-1) of the ARDL model with a lag structure (1,0,2,2,2) exhibits a negative and highly significant coefficient (-1.2988; $p = 0.001$), confirming the existence of a long-term adjustment mechanism between CO₂ emissions and their determinants. The negative sign indicates that deviations from the long-term equilibrium are corrected in the following period, while its magnitude suggests a rapid and more than proportional adjustment, implying that the system converges to equilibrium, even with the possibility of over-adjustment, before stabilising (Ahmad et al., 2022). The high statistical significance of the ECT supports the cointegration between the variables and validates the dynamic consistency of the model, strengthening the econometric robustness of the long-term results associated with the Environmental Kuznets Curve (Okere et al., 2022).

Table 7. Long-term and short-term estimates

Block	Variable	Coefficient	Error Std.	p-value
Adjustment (Error Correction Term)	EC _{t-1} (ln CO ₂)	-1.2988	0.2845	0.001***
Long-run	lnGDP_pc	0.627	0.418	0.007***
	lnGDP ² _pc	-1.902	1.085	0.017**
	lnE_pc	0.068	0.201	0.041**
	lnIPC	-0.105	0.119	0.386
Short-run	ΔlnGDP ² _pc	5.4167	3.0337	0.102
	ΔlnE_pc	-1.5937	0.6106	0.024**
	ΔlnIPC	-0.9743	0.4159	0.039**
	Constant	7.3964	2.7740	0.022**

Note: Long-run (LR) coefficients are reported. Statistical significance is evaluated using the t-statistic. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Variables are expressed in natural logarithms.

Source: own elaboration.

In the long term, the results of the ARDL model empirically confirm the Environmental Kuznets Curve, demonstrating a non-linear relationship between economic growth and CO₂ emissions (Tagwi, 2022). Per capita income and its quadratic term are statistically significant and have opposite signs, indicating that economic growth initially increases environmental degradation, but that this effect reverses at higher levels of development, forming an inverted U-shaped trajectory consistent with the Kuznets hypothesis (Romanowska et al., 2021). Furthermore, energy consumption has a positive and significant effect on emissions, establishing itself as a structural determinant of environmental deterioration in the long term. In contrast, the Corruption Perceptions Index is not statistically significant, suggesting that, in the long term, the perception of corruption does not play a determining role in emissions dynamics, remaining outside the structural relationship between economic growth and environmental degradation (Haseeb & Azam, 2021).

In the short term, ARDL model estimates, expressed as first differences, indicate that variations in economic growth, captured by the quadratic term of GDP per capita, do not generate statistically significant effects on CO₂ emissions, suggesting that transitory economic changes do not immediately translate into environmental pressures. In contrast, variations in energy consumption have a significant effect on emissions, demonstrating that short-term adjustments in energy use directly impact environmental dynamics. Similarly, changes in the Corruption Perceptions Index (CPI) show a statistically significant effect in the short term, indicating that variations in institutional quality and perceived levels of corruption immediately influence emissions behaviour (Yang et al., 2022).

Taken together, the short and long-term results show that the relationship between economic growth and environmental degradation in Ecuador was predominantly structural and long-term, in line with the Environmental Kuznets Curve (Dilanchiev et al., 2024). While the dynamics of economic growth exhibited a clearly defined nonlinear pattern only in the long term, short-term effects were dominated by institutional and energy factors. This evidence suggests that sustained emissions reductions depended not on short-term adjustments, but on structural improvements in institutional quality and profound transformations in the energy mix and the pattern of economic growth (Michailidis et al., 2025).

4.3. Results of the Causality Analysis

The Toda and Yamamoto (1995) procedure was adopted to analyse the causal structure among the variables within a multivariate framework. This approach was selected because it allowed for the estimation of a Vector Autoregressive (VAR) model in levels while avoiding potential biases associated with the integration properties of the variables. By augmenting the lag length of the VAR model according to the maximum order of integration among the series, the method ensured the validity of the statistical inference derived from the Wald tests (Kripfganz & Schneider, 2023).

The implementation of the Toda–Yamamoto methodology involved selecting the optimal lag length using standard information criteria and estimating an augmented VAR model in levels. Causality was then assessed through Wald-type restrictions applied to the coefficients of the lagged variables, with statistical significance evaluated using Chi-square statistics and their corresponding p-values (Sharaf et al., 2025).

Causality was evaluated based on the following null hypothesis:

- **H₀:** X does not Granger-cause Y.

The decision rule was based on the p-value associated with the Wald test. When the p-value is lower than 0.05, the null hypothesis is rejected, indicating statistical evidence of causality from X to Y. Conversely, when the p-value is greater than 0.05, the null hypothesis cannot be rejected, suggesting that no causal relationship exists in the specified direction (Chen et al., 2023).

Table 8 presents the results of the causality tests based on the Toda-Yamamoto approach. The table reports the Chi-square, degrees of freedom, and corresponding p-values associated with each null hypothesis, allowing the identification of statistically significant causal relationships among the variables included in the model.

Table 8. Granger causality test results

Dependent variable	Explanatory variable	χ^2	Df	p-value
ln_CO ₂	ln_GDP	2.100	2	0.350
ln_CO ₂	ln_Energy consumption	3.372	2	0.185
ln_CO ₂	ln_Corruption Index	3.055	2	0.217
ln_CO ₂	ln GDP ²	9.853	2	0.007**
ln_GDP	ln_CO ₂	1.968	2	0.374
ln_Energy consumption	ln_GDP	13.050	2	0.001***
ln_Corruption Index	ln_Energy consumption	15.833	2	0.000***
ln GDP ²	ln_Corruption Index	13.208	2	0.001***

Note: * p < 0.10, ** p < 0.05, *** p < 0.01.

Source: own elaboration.

The results indicate that carbon dioxide emissions per capita were not causally affected by GDP per capita, energy consumption per capita, or the corruption perception index, as the null hypotheses cannot be rejected at the 5% significance level. However, a statistically significant causal effect from the squared GDP term to CO₂ emissions was detected, suggesting the presence of nonlinear dynamics in the relationship between economic activity and environmental degradation (Thai Hung, 2022).

Additionally, the findings revealed several significant causal relationships among the explanatory variables. Energy consumption per capita exhibited a causal effect on GDP per capita, while both energy consumption and GDP per capita were found to causally influence the corruption perception index. Furthermore, the squared GDP term showed causal effects on energy consumption and the corruption perception index, highlighting the relevance of nonlinear economic effects within the system. In general, these results emphasize the complex and interconnected causal structure among economic, institutional, and environmental variables.

5. Conclusion

This study reassessed the validity of the Environmental Kuznets Curve (EKC) hypothesis for Ecuador over the period 2000–2024 using the ARDL approach and the Toda-Yamamoto causality framework. The econometric evidence confirmed the existence of a stable long-run relationship between CO₂ emissions, economic growth, energy consumption, and institutional quality. The significant and negative error correction term indicated a rapid adjustment toward long-run equilibrium, validating the dynamic consistency and cointegration of the model.

The long-term ARDL estimates provided robust empirical support for the EKC hypothesis. GDP per capita and its squared term were both statistically significant and exhibited opposite signs, confirming a nonlinear inverted U-shaped relationship between economic growth and CO₂ emissions. This result suggests that, while economic expansion initially increases environmental degradation, higher levels of income were associated with a reversal of this trend. In contrast to previous findings, energy consumption emerges as a significant and positive determinant of emissions in the long run, highlighting its structural role in environmental deterioration. Institutional quality, proxied by the Corruption Perceptions Index, did not show a statistically significant long-term effect, indicating that governance does not constitute a structural driver of emissions over time.

Short-term dynamics differ markedly from long-term behaviour. Economic growth does not exert a statistically significant short-term effect on CO₂ emissions, implying that temporary fluctuations in income do not immediately translate into environmental pressures. However, short-term variations in energy consumption and institutional quality significantly affect emissions, suggesting that changes in energy use and governance conditions have immediate environmental implications. These results underline that short-term emissions dynamics in Ecuador were driven primarily by energy and institutional factors rather than by income growth itself.

The causality analysis based on the Toda-Yamamoto methodology reinforces the presence of nonlinear mechanisms in the growth-environment nexus. While no direct causal effects were found from GDP per capita, energy consumption, or institutional quality to CO₂ emissions, a statistically significant causal relationship from the squared GDP term to emissions was identified. This finding confirmed that the impact of economic activity on environmental outcomes operated through nonlinear channels rather than linear growth effects. Additionally, the detected causal links among energy consumption, economic growth, and institutional quality revealed a complex and interconnected system in which economic scale effects influenced both energy use and institutional dynamics.

In general, the results indicated that the relationship between economic growth and environmental degradation in Ecuador was predominantly structural and long-term in nature. Achieving sustained reductions in CO₂ emissions requires policies that go beyond short-term economic adjustments, focusing instead on transforming the energy matrix, improving energy efficiency, and strengthening institutional frameworks. These structural reforms are essential for consolidating the downward phase of the EKC and advancing toward an environmentally sustainable growth path.

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