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Dynamic Perspective of the Evolution of the Environmental Kuznets Curve in Ecuador and Mexico

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Abstract: The Environmental Kuznets Curve (EKC) posits that environmental degradation increases during the early stages of economic development and decreases once a certain income level is reached. Ecuador and Mexico illustrate contrasting patterns within this framework: the former relies heavily on natural resources, while the latter has a more diversified economy, albeit with persistent environmental challenges. The aim of this study is to compare the validity of the EKC in both countries during the period 2007–2024 by analyzing the relationship between economic growth and CO₂ emissions using spatial SAR and SEM models. Recent subnational data were transformed into logarithmic form to capture regional variations and facilitate the interpretation of economic and environmental relationships. The results indicate that Ecuador remains in the ascending phase of the EKC, whereas Mexico shows a trajectory trending toward an inverted U-shape, suggesting that the country may have reached its turning point in certain regions. Furthermore, in Ecuador, pollution exhibits strong spatial interdependence among provinces, mainly associated with the concentration of development in extractive areas. In contrast, although spatial

dependence is also observed in Mexico, it is less pronounced and reflects a more dispersed and heterogeneous distribution of pollutant emissions

1. INTRODUCTION

In recent decades, the sustainability of economic growth has become a central topic in economic and environmental research, giving rise to multiple analytical frameworks aimed at explaining the relationship between economic development and environmental degradation. Among these approaches, the Environmental Kuznets Curve (EKC) has gained particular relevance by proposing a non-linear relationship between per capita income and environmental degradation (Grossman & Krueger, 1995). Building on Kuznets' original hypothesis (Kuznets, 1955), the EKC suggests that pollutant emissions increase during the early stages of economic development but tend to decline once a certain income threshold is reached. Nevertheless, the empirical applicability of this hypothesis has been widely debated. Empirical evidence provided by studies such as Sarkodie and Strezov (2020) and Kangyin et al. (2018) indicates that the validity of the EKC depends both on the type of pollutant analyzed and the institutional context in which economic growth occurs.

Al-Mulali et al. (2015) argue that persistent pollutants such as CO₂ do not always conform to the theoretical EKC pattern, while Xingming et al. (2021) emphasize that institutional weaknesses may prevent countries from reaching the turning point required to reverse environmental degradation. In this context, Ecuador and Mexico constitute particularly relevant cases for examining the dynamic validity of the EKC, as both countries exhibit distinct development models while facing similar sustainability challenges. Ecuador maintains a highly resource-dependent economy, particularly reliant on oil extraction, which shapes its productive structure and constrains its transition toward less emission-intensive development paths (Larrea & Warnars, 2009; Cevallos-Mina et al., 2024). Mexico, by contrast, displays a more diversified economy, supported by a solid manufacturing base integrated into international value chains (Vázquez-López, 2023). Nevertheless, this structural advantage has not necessarily resulted in lower environmental pressure.

Environmental challenges such as air pollution in metropolitan areas, the overexploitation of aquifers, and the degradation of coastal ecosystems indicate that economic growth has not always followed a sustainable path (Blackman et al., 2015; Figueroa et al., 2021). These contrasts provide a valuable basis for examining how factors such as productive structure, institutional quality, and public policies influence the specific form that the EKC adopts in both countries. In this context, the main objective of this study is to compare the validity of the

Environmental Kuznets Curve (EKC) in Ecuador and Mexico over the period 2007–2024, incorporating a spatial perspective that enables the identification of regional CO₂ emission patterns and the characterization of structural differences in the relationship between economic growth and environmental degradation.

1.1. The Kuznets Environmental Curve (EKC)

The Environmental Kuznets Curve (EKC) emerges as an environmental extension of Kuznets' original hypothesis (Kuznets, 1955), which established a relationship between economic development and income inequality. Grossman and Krueger (1995) later adapted this framework to the environmental context, arguing that during the early stages of economic growth, pollution levels tend to increase, but once a certain per capita income threshold is reached, environmental degradation begins to decline. This hypothesis has been extensively discussed and empirically tested in the literature. Sarkodie and Strezov (2020) emphasize that the EKC does not hold universally, while Xingming et al. (2021) argue that institutional factors play a decisive role in determining its validity, particularly in emerging economies. Similarly, Al-Mulali et al. (2015) contend that the shape of the EKC depends on the specific environmental indicator employed, whereas Dong et al. (2018) highlight that globalization processes and environmental policies can significantly alter the trajectory of the curve. Complementarily, Shahbaz et al. (2019) suggest that the transition toward cleaner economic structures is largely driven by development-induced structural transformation and regulatory reforms.

In this framework, the EKC is commonly conceptualized as a three-stage process. The first stage is characterized by environmental deterioration associated with industrialization and rapid economic expansion. The second stage corresponds to income levels at which societies are increasingly able to implement environmental regulations and mitigation policies. Finally, the third stage involves a reduction in environmental degradation driven by technological innovation and growing ecological awareness (Murshed et al., 2021). Tangato (2025) highlights the adoption of clean technologies as a crucial element in this final phase, while Ahmed et al. (2020) emphasize the role of environmental education in accelerating the transition toward more sustainable development paths. However, compliance with this theoretical pattern is not guaranteed. Usman et al. (2022) argue that in many developing countries, corruption and weak institutional frameworks hinder the achievement of the EKC turning point. By contrast, Acheampong et al. (2021) contend that technological innovation plays a key role in decoupling economic growth from environmental degradation, although its effective implementation remains uneven across countries.

Several studies have raised conceptual critiques of the Environmental Kuznets Curve. Destek and Sarkodie (2019) question the assumption that economic development alone necessarily leads to environmental improvement. Similarly, Kaika and Zervas (2013) argue that the EKC framework fails to account for the cumulative and long-term impacts of environmental degradation, particularly in the context of climate change. Sinha et al. (2020) further contend that the EKC overlooks the role of international institutions in shaping global environmental governance. In addition, Paramati et al. (2018) warn that certain pollutants, such as plastic waste, do not decline with higher income levels. Dong et al. (2018) emphasize that national and international policy interventions can significantly alter the trajectory implied by the EKC. Finally, Al-Mulali et al. (2015) note that empirical outcomes are highly sensitive to the type of pollutant analyzed, which limits the generalizability of the EKC across different environmental contexts.

1.2. Studies in several countries

Empirical studies on the Environmental Kuznets Curve have employed a wide range of environmental indicators to test its validity. The ecological footprint has been used to measure human pressure on ecosystems, and Charfeddine and Mrabet (2017) demonstrate its relevance in countries with a high dependence on natural resources. Carbon dioxide (CO₂) emissions remain the most commonly used indicator, with Khan et al. (2020) showing that CO₂ emissions tend to increase during the early stages of economic growth but can be reduced through the implementation of appropriate environmental policies. Goulart et al. (2023) find that, in Latin America, agricultural expansion has sustained critical levels of deforestation, even in economies that have surpassed the medium stage of development. Rakpho and Yamaka (2021) introduce an alternative indicator—water pollution by heavy metals—whose environmental persistence and weak regulatory frameworks prevent it from following the theoretical EKC pattern. Moreover, Jahanger et al. (2022) emphasize that environmental indicators must be adapted to regional contexts in order to avoid distortions in comparative analyses.

The role of economic development-related variables has also been extensively examined in the EKC literature. Alvarado et al. (2021) note that per capita income is commonly used as a proxy for development levels, although its relationship with pollution differs depending on the type of pollutant considered. Dogan et al. (2020) demonstrate that in countries with a high penetration of renewable energy sources, the declining phase of the EKC tends to be more pronounced. In contrast, Adams and Acheampong (2019) observe that in several African economies, industrialization in the absence of adequate regulatory frameworks leads to increased

pollution levels. Li et al. (2023) argue that international trade directly influences environmental outcomes, particularly when countries exporting energy-intensive goods effectively outsource their emissions. Furthermore, Catalán (2021) emphasizes the importance of rigorous monitoring of greenhouse gas emissions to accurately assess climate commitments, while Wackernagel et al. (2017) highlight the ecological footprint as a comprehensive indicator that integrates emissions, resource consumption, and biological regeneration capacity.

In addition, more recent studies reinforce the need to adapt the EKC framework to specific regional realities. Goulart et al. (2023) emphasize that deforestation should be analyzed through the lens of persistent agricultural expansion, while Wang et al. (2023) demonstrate that in Southeast Asian countries, rapid industrialization generates a complex relationship between economic growth and ecological damage, in which the environmental curve may not evolve as theoretically expected. Shahbaz et al. (2019) further reiterate that the trajectory of the EKC is strongly mediated by a country's institutional capacity to design and enforce effective environmental regulations. Finally, Stern (2004) stresses that historical analyses of emissions and sustainability provide a more accurate assessment of national environmental trajectories and potential turning points, highlighting the need to strengthen policy frameworks based on observed environmental outcomes.

1.3. Relevance of spatial modelling

Recent advances in economic–environmental analysis have allowed the EKC to be examined from a dynamic perspective, thereby overcoming the limitations inherent in traditional static models. Unlike approaches that focus exclusively on contemporaneous relationships between variables, dynamic models incorporate temporal evolution and the cumulative effects of economic growth on environmental outcomes (Okullo, 2020; Pei et al., 2021). This framework makes it possible to identify feedback mechanisms, such as the impact of environmental degradation on future growth potential (Herrera et al., 2024). In addition, dynamic models facilitate the analysis of the roles of technological innovation and institutional quality in shaping a country's long-term environmental trajectory (Meckling & Nahm, 2019; Medina-Rivas et al., 2022).

Thus, the EKC has evolved into an analytical framework that no longer seeks to validate a single curve shape, but rather to identify the conditions under which environmentally sustainable development can be achieved. A particularly important aspect of this comparative analysis is the selection of appropriate indicators to capture the relationship between economic growth and environmental degradation. Variables such as GDP per capita, CO₂ emissions, deforestation, and energy consumption are among the most frequently used measures

in the EKC literature (Khan et al., 2020; Alvarado et al., 2021). In the case of Ecuador, energy-related emissions and the loss of Amazonian forests constitute critical indicators (Chen et al., 2022), whereas in Mexico, factors such as urban pollution and the degradation of agricultural and water ecosystems are especially relevant (Renner, 2018; Percastre et al., 2024).

The validity and comparability of these indicators, according to Stern (2004) and Wackernagel et al. (2017), depend on both their statistical quality and their contextual relevance. Consequently, the selection of indicators reflects not only methodological considerations but also policy-related criteria, reinforcing their relevance in dynamic and comparative analyses.

1.4. Graphical representation of the Kuznets Environmental Curve

In Ecuador, the distribution of provinces in the development–emissions space (Figure 1) shows a clear concentration in the ascending phase of the Environmental Kuznets Curve (EKC), with no evidence of a transition toward its declining phase at the aggregate level. This pattern is closely linked to the country’s strong dependence on oil and its primary-export economic model, in which growth continues to rely on emission-intensive activities (Cevallos-Mina et al., 2024). In addition, institutional weaknesses and the budgetary constraints of the Ministry of Environment have significantly limited the country’s capacity to design and implement effective environmental policies, a situation also observed in comparable developing-country contexts (Sinha et al., 2020; Usman et al., 2022).

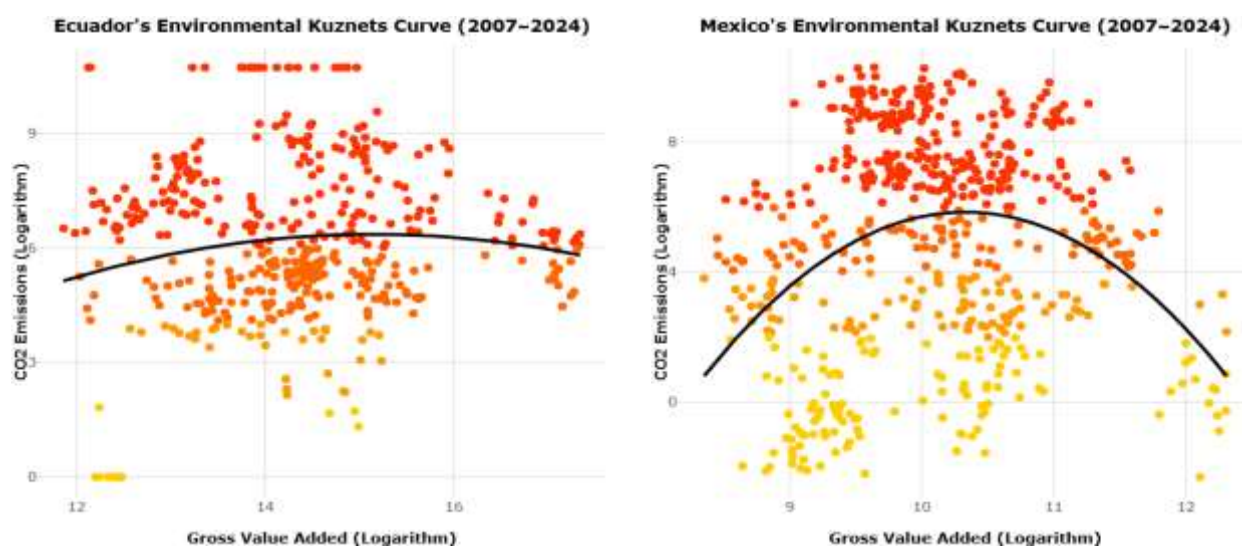


Fig. 1: Kuznets Environmental Curve in Ecuador and Mexico (2007–2024)

Source: Prepared by the authors in the Observatory of Economic and Financial Sustainability (OSEF, 2025).

According to EKC theory, in its initial stage economic growth typically generates higher levels of pollution due to industrialization processes under weak or incipient environmental regulations (Shahbaz et al., 2022). Consistent with this framework, the evidence indicates that Ecuador remains in the ascending phase of the EKC, reflecting a persistent dependence on extractive activities and a limited capacity for environmental management (Cevallos-Mina et al., 2024). In resource-based economies with weak institutional structures, economic growth tends to intensify pollution levels (Almeida et al., 2024). Similarly, in contexts of low institutional development, environmental pressures increase as a result of the absence of effective and sustainable governance mechanisms (Jeetoo, 2023). Overall, Ecuador's trajectory supports the premise that, without productive diversification and effective environmental policies, the EKC continues along its upward path, driven by an economic model based on the intensive exploitation of natural resources.

In contrast, in Mexico the regional distribution of the EKC graph suggests a trajectory that tends toward an inverted U-shape, indicating that the country may have reached its turning point in certain regions. This pattern is associated with a more diversified economic structure and a stronger institutional capacity to implement environmental policies, particularly reflected in the promotion of renewable energy during the 2013–2018 period (Percastré et al., 2024). This behavior is consistent with previous findings showing that in countries with solid regulatory frameworks, technological progress, and widespread use of clean energy, the Environmental Kuznets Curve tends to display a more pronounced declining phase (Dogan et al., 2020; Acheampong et al., 2021).

In this context, the empirical results confirm that Mexico displays an EKC with signs of partial decoupling between economic growth and environmental degradation, explained by institutional consolidation, productive diversification, and progress in energy efficiency. Mahmoodi and Dahmardeh (2022) argue that countries with greater regulatory capacity tend to generate more sustainable environmental trajectories, while Almeida et al. (2024) emphasize that middle-income economies with mixed productive structures can reduce ecological pressure without halting growth. Thus, the Mexican case demonstrates a gradual transition toward a sustainable development model, consistent with the theoretical predictions of the Environmental Kuznets Curve.

In countries such as Ecuador and Mexico, where industrial zones coexist with active volcanic regions, understanding these dynamics through spatial analyses and graphical representations is essential for assessing environmental impacts and informing control and mitigation policies.

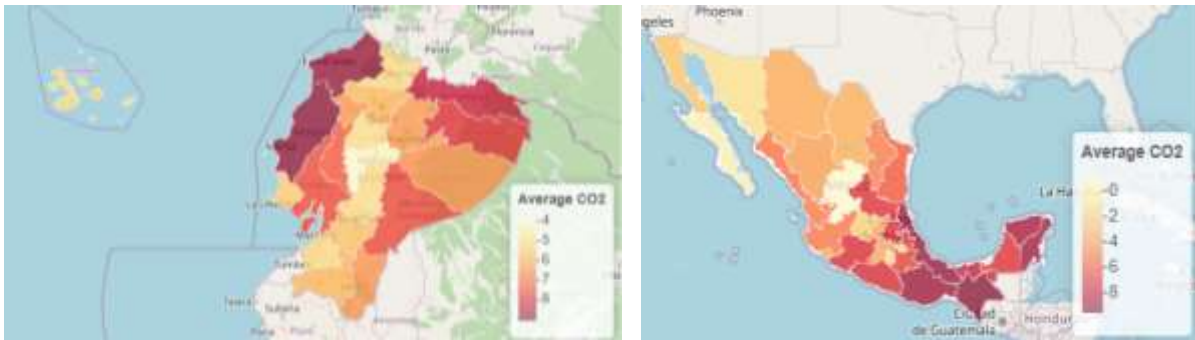


Fig. 2: Spatial distribution of CO₂ emissions in Ecuador and Mexico (2007).

Note: Areas of higher colour intensity correspond to higher levels of CO₂.

Source: Observatorio Social, Económico y Financiero (OSEF, 2025).

Both Ecuador and Mexico exhibit CO₂ emission patterns consistent with the ascending phase of the Environmental Kuznets Curve, in which economic growth drives environmental degradation. In 2024 (Figure 4), the spatial distribution of emissions in Ecuador shows particularly high levels in the Amazonian provinces (Pastaza, Orellana, Sucumbíos, Morona Santiago) and in coastal provinces such as Guayas and Manabí, while some areas in the Sierra display relatively lower values. This pattern may indicate an incipient transition toward the declining phase of the Environmental Kuznets Curve in certain territories. The creation of the Ministry of Environment, Water, and Ecological Transition points to a process of institutionalizing sustainability. However, recent studies indicate that the services sector—despite its low direct emissions—accounts for up to 35.5% of national emissions due to indirect effects, thereby limiting deeper structural transformation (Buenaño et al., 2023). Overall, the evidence suggests that although progress has been made in formalizing environmental policy, the extractivist economic model continues to strongly shape environmental trajectories—consistent with Larrea and Warnars (2009) and Sinha et al. (2020), who highlight the structural limitations of the EKC in resource-dependent economies.

In Mexico, emission levels remain high in the southeast (Chiapas, Tabasco, Campeche, Quintana Roo, Yucatán, Veracruz) and in the central industrial zones (Mexico City, State of Mexico, Puebla, Hidalgo), with few positive changes compared to 2015. This stagnation can be explained by the suspension of clean energy auctions and the promotion of large-scale polluting projects, such as the Dos Bocas Refinery, which—according to Renner (2018) and Fujii et al. (2024)—have weakened environmental governance under the current administration. Despite some localized advances—such as the emission reduction program in Jalisco—the 75% cut in the environmental budget has constrained any structural attempt at ecological transition. This stagnation confirms Kaika and Zervas (2013)'s critique of the fallacy that economic growth automatically leads to

environmental improvements and reinforces the argument of Medina-Rivas et al. (2022) that strong institutions and coherent policies are essential for sustainable development.

2. MATERIALS AND METHODS

This study adopts a quantitative and comparative research design to examine the relationship between economic development and carbon dioxide (CO₂) emissions in Ecuador and Mexico, grounded in the theoretical framework of the Environmental Kuznets Curve (EKC). The methodological sequence comprises: (i) description of the dataset; (ii) operationalization of variables; (iii) variable construction and specification of the spatial weights matrix (W) to ensure cross-country comparability; and (iv) econometric specification and estimation of spatial panel models (SAR and SEM).

2.1. Data Description and Panel Structure

The empirical analysis relies on secondary data compiled from official national and international statistical sources, consisting of annual subnational observations for Ecuador and Mexico. In Ecuador, the unit of analysis is the province, whereas in Mexico it is the federal state. The study period spans 2007–2024, corresponding to the most recent years for which statistically comparable subnational information is simultaneously available for both economies, thereby ensuring methodological consistency and temporal homogeneity in the construction of the panel.

The resulting dataset is structured as an annual panel with territorial units (i) observed over time (t). This panel structure increases the number of observations and improves the statistical efficiency and robustness of the econometric estimates. The subnational level of disaggregation is a core component of the empirical design, as it enables the identification of regional heterogeneity in total CO₂ emissions, emissions intensity, value-added dynamics, and access to basic infrastructure. Compared with nationally aggregated studies, the subnational approach reduces aggregation bias and allows the detection of differentiated spatial patterns within each country.

Cross-country comparability between Ecuador and Mexico is ensured through the conceptual harmonization of variables and the application of equivalent statistical definitions across jurisdictions. Detailed information on data sources, units of measurement, and expected coefficient signs is reported in Table 1, ensuring traceability, methodological transparency, and reproducibility of the empirical analysis.

Table 1. Description of variables.

Variable Type	Variable	Description	Unit of Measure	Source: Ecuador	Source: Mexico	Expected Sign
Endogenous	CO2 emissions	Total CO ₂ emissions generated in territorial unit <i>i</i> at time <i>t</i> .	Metric tons (t CO ₂)	Global Forest Watch (GFW)	Global Forest Watch (GFW)	N/A
	CO2 Intensity	Emissions intensity: CO ₂ emissions per unit of economic output.	t CO ₂ / USD million	Calculated from GFW and BCE	Calculated from GFW and INEGI	(+)
Exogenous	GVA	Total Gross Value Added (constant USD millions).	Constant USD Million	Central Bank of Ecuador (BCE)	National Institute of Statistics and Geography (INEGI)	(+)
	GVA ²	Quadratic term of GVA to capture nonlinearities.	(USD million) ²	Central Bank of Ecuador (BCBE)	National Institute of Statistics and Geography (INEGI)	(-)
	H ₂ O _{Red}	Households with piped water access through the public network.	Percentage (%)	Ministry of Economic and Social Inclusion (MIES)	National Institute of Statistics and Geography (INEGI)	(-)

Source: Prepared by authors.

Note: The sources are presented differentiated according to their national origin, which facilitates the comparison between Ecuador and Mexico and ensures the traceability of the data used.

2.2. Definition and Measurement of Variables

2.2.1. Dependent Variable: CO₂ Emissions

The dependent variable is territorial carbon dioxide emissions, denoted as CO_{2it} , measured in metric tons (tCO₂) at the subnational level. This variable captures the environmental pressure associated with economic activity in territorial unit *i* at time *t*. For econometric estimation, the natural logarithm of total emissions is employed to improve numerical stability and mitigate potential heteroskedasticity:

$$\ln(CO_{2it})$$

The choice between level and logarithmic specifications was guided by econometric criteria derived from goodness-of-fit tests and spatial dependence diagnostics, ensuring consistency with the statistical properties of the data and the theoretical structure of the model.

2.2.2. Independent Variables

CO₂ Intensity

CO₂ intensity measures the amount of carbon emissions generated per unit of economic output and serves as an indicator of the environmental efficiency of production at the subnational level. Higher values indicate that a territory produces the same level of value added with a greater emissions burden, whereas lower values are consistent with cleaner or more efficient production structures.

For each territorial unit i and year t , CO₂ intensity is constructed as:

$$CO2\ Intensity_{it} = \frac{CO2_Emissions_{it}}{GVA_{it}}$$

Where $CO2_{it}$ denotes total CO₂ emissions (metric tons) and GVA_{it} represents Gross Value Added measured in constant USD millions.

Gross Value Added (GVA)

Gross Value Added (GVA) is used as the proxy for territorial economic activity at the subnational level and is expressed in constant U.S. dollars (USD millions) to ensure temporal comparability across the study period. The variable is initially obtained in levels (GVA_{it}) from official sources and then used to construct a nonlinear term in levels:

$$GVA_{it}^2 = (GVA_{it})^2$$

This quadratic transformation is introduced to allow for nonlinearities in the relationship between economic activity and emissions within the econometric specification. For estimation purposes, GVA is also incorporated in logarithmic form, $\ln(GVA_{it})$ to reduce scale effects across territories and improve numerical stability. Thus, the empirical models combine the log-transformed activity indicator with a nonlinear output term in levels

2.2.3. Control Variable: H2ORed

The percentage of households with access to piped water from the public network, denoted as $H2ORed_{it}$ is included as a control variable at the subnational level (provinces in Ecuador and federal states in Mexico). This indicator captures differences in basic infrastructure and territorial development that may be correlated with production patterns and, indirectly, with emission dynamics.

In the econometric specification, $H2ORed_{it}$ enters in levels (percentage points) to control for structural heterogeneity in access to public services and to reduce omitted-variable bias when estimating the relationship between economic activity and CO₂ emissions.

2.3. Data Processing, Variable Construction, and Spatial Weights (W)

Before estimation, the series were checked to ensure temporal consistency, homogeneity of measurement units, and methodological compatibility across statistical sources, thereby supporting cross-country comparability. Geographic coordinates (longitude and latitude) were compiled and validated for each subnational unit, as they are required to construct the spatial weights matrix used in spatial diagnostics and spatial econometric estimation.

2.3.1. Variable construction and transformations

Two derived variables were constructed for the econometric analysis. First, the quadratic output term was generated as:

$$GVA_{it}^2 = (GVA_{it})^2$$

Second, CO₂ intensity was computed as the ratio between total emissions and economic activity:

$$CO2\ Intensity_{it} = \frac{CO2_Emissions_{it}}{GVA_{it}}$$

Logarithmic transformations were then applied to selected variables used in the econometric specification to stabilize variance and facilitate interpretation in elasticity terms. Specifically, the analysis uses $\ln(CO2_Emissions)_{it}$, $\ln(GVA_{it})$ and $\ln(CO2_Intensity)_{it}$. The quadratic term GVA_{it}^2 and the infrastructure control $H2ORed_{it}$ enter the specification in levels.

2.3.2. Data completeness and spatial referencing

Data completeness was verified for all variables included in the econometric specification. Observations with missing geographic coordinates were excluded prior to spatial modeling to ensure that all units included in the estimation could be spatially referenced and consistently connected through the spatial weights matrix. The final estimation samples correspond to the sets of subnational units and years with complete information required for panel estimation and spatial diagnostics.

2.3.3. Spatial weights matrix (W)

Spatial dependence was modeled using a distance-based inverse-distance spatial weights matrix W , constructed from the longitude and latitude coordinates of subnational units. The baseline matrix assigns weights according to the inverse of inter-territorial distance within a fixed distance band:

$$W_{ij} = \begin{cases} \frac{1}{d_{ij}} & \text{si } 0 < d_{ij} \leq 100 \\ 0 & \text{otherwise} \end{cases} \quad (i \neq j), \quad W_{ii} = 0$$

The matrix was row-standardized so that each row sums to one. This specification restricts spatial interactions to neighbors located within a maximum radius of 100 (distance units consistent with the coordinate-based distance calculation) and ensures comparability of spatial effects across territorial units. The resulting W matrix was used to perform spatial dependence diagnostics and to estimate spatial lag (SAR) and spatial error (SEM) models.

2.4. Econometric Specification and Spatial Panel Models (SAR/SEM)

This section presents the spatial econometric specifications used to estimate CO₂ emissions at the subnational level in Ecuador (provinces) and Mexico (federal states). Models are estimated separately for each country to account for potential structural differences in spatial interaction mechanisms.

2.4.1. General spatial specifications

To capture territorial interdependence in CO₂ emissions, two alternative spatial specifications were estimated: a Spatial Autoregressive-type specification (SAR) and a Spatial Error Model (SEM), using the previously defined spatial weights matrix W .

The spatial autoregressive-type specification is expressed as:

$$Y_{it} = \rho W Y_{it} + X_{it}\beta + \varepsilon_{it}$$

Where Y_{it} represents the logarithm of CO₂ emissions, $\rho W Y_{it}$ is the spatial lag of the dependent variable, ρ measures the intensity of direct spatial dependence $X_{it}\beta$ denotes the matrix of explanatory variables, β is the associated parameter vector, and ε_{it} is the random error term.

The SEM model is defined as:

$$Y_{it} = X_{it}\beta + u_{it}, \quad u_{it} = \lambda W u_{it} + \varepsilon_{it}$$

Where λ captures spatial autocorrelation in the error term. In this case, territorial dependence operates through spatially correlated unobserved shocks rather than through the dependent variable itself. Both

specifications are estimated by maximum likelihood, and model selection is based on information criteria and statistical significance tests of the spatial parameters.

2.4.2. Spatial Autoregressive Model (SAR)

The Spatial Autoregressive (SAR) specification incorporates the spatial lag of CO₂ intensity in order to capture direct spillover effects transmitted through neighboring regions' environmental efficiency. The general model is expressed as:

$$\ln CO2_Emissions = \alpha_i + \beta_1 \rho W \ln(CO2_Intensity)_{it} + \beta_2 \ln(GVA)_{it} + \beta_3 (GVA)_{it}^2 + \beta_4 (H2ORed)_{it} + u_{it} + \lambda_{it} + \varepsilon_{it}$$

The specification corresponds to a spatial lag of an explanatory variable (SLX-type model), where spatial spillovers operate through neighboring regions' CO₂ intensity rather than through the dependent variable itself; in this framework ρ measures the magnitude of spatial interaction associated with neighboring regions CO₂ intensity, α_i represents territorial fixed effects λ_t captures common time effects, and ε_{it} is the idiosyncratic error term. For model stability and to ensure a well-defined spatial process, the spatial parameter must satisfy the condition $|\rho| < 1$

2.4.3. Spatial error Model (SEM)

The Spatial Error Model assumes that spatial dependence operates through unobserved components rather than through an explicitly lagged explanatory variable. The specification is:

$$\ln CO2_Emissions = \alpha_i + \beta_1 (\ln GVA)_{it} + \beta_2 (GVA)_{it}^2 + \beta_3 (H2ORed)_{it} + u_{it} + \lambda_{it} + \varepsilon_{it}$$

with the error structure defined as:

$$u_{it} = \lambda W u_{it} + \varepsilon_{it}$$

Where λ_t captures spatial autocorrelation in the residuals and ε_{it} is a white-noise disturbance term.

3. RESULTS AND DISCUSSION

This section reports the empirical results for Ecuador and Mexico and discusses their economic and spatial interpretation within the Environmental Kuznets Curve (EKC) framework. It compares the SAR and SEM

specifications and evaluates whether the estimated relationship exhibits a turning (inflection) point in CO₂ emissions

3.1. Validation of Spatial Dependency Tests

Table 2 presents the results of the spatial dependency tests applied to CO₂ emissions in Ecuador and Mexico. For both countries, the values of Moran's I and the Lagrange Multiplier tests—for the spatial error model and the spatial lag model—are statistically significant ($p < 0.01$), confirming the presence of spatial autocorrelation in the distribution of emissions.

Table 2. Spatial Dependence between Ecuador vs. Mexico

Country:	Test:	Statistics:	Valor P
Ecuador	Spatial error:		
	Moran Index	14.363	0.000
	Lagrange multiplier	40.057	0.000
	Robust Lagrange multiplier	9.861	0.002
	Spatial lag:		
	Lagrange multiplier	137.344	0.000
	Robust Lagrange multiplier	107.148	0.000
México	Spatial error:		
	Moran Index	39.551	0.000
	Lagrange multiplier	408.348	0.000
	Robust Lagrange multiplier	193.306	0.000
	Spatial lag:		
	Lagrange multiplier	271.186	0.000
	Robust Lagrange multiplier	56.143	0.000

Note: With a significance level of 5%. $p < 0,01$, ** $p < 0,05$, * $p < 0,1$

In the case of Ecuador, although the test statistics are high, their values are slightly lower than those observed for Mexico. This indicates a strong, albeit less intense, spatial dependence, meaning that emissions in one province are influenced by emissions in neighboring provinces. This pattern is consistent with the concentration of emissions in extractive zones such as the Amazon region and the Coast. Such dependence reflects how the extractivist development model tends to spatially cluster environmental impacts and aligns with the findings of Larrea and Warnars (2009) and Cevallos-Mina et al. (2024), who identify a territorial degradation pattern associated with oil-based development.

In Mexico, the values are even higher, indicating a very strong degree of spatial dependence. This suggests that CO₂ emissions exhibit greater continuity and concentration across regions, possibly driven by the presence of industrial corridors (e.g., Monterrey–Toluca) and the structural weight of the manufacturing sector in specific areas (Elizondo et al., 2025). These results are consistent with the findings of Blackman et al. (2015) and

Vázquez-López (2023), who emphasize that intensive industrialization has generated regional pollution hotspots affecting contiguous territories. At a theoretical level, this spatial dependence reinforces the arguments of Herrera et al. (2024) regarding the need to incorporate dynamic and regionalized approaches into EKC analysis, as the environmental effects of economic growth are neither homogeneous nor spatially independent.

3.2. Spatial Model Analysis SAR (Spatial Autoregressive Error)

Table 3 presents the results of the Spatial Autoregressive (SAR) model, which incorporates spatial dependence into the analysis of the relationship between economic growth and CO₂ emissions. For both countries, the estimates reveal a non-linear relationship between economic development and pollution levels, thereby confirming the theoretical form of the Environmental Kuznets Curve (EKC).

Table 3. Spatial Error Model (SAR) between Ecuador vs. Mexico

Country:	Variable:	Coefficient:	Standard Error:	Z-Value:	P value	[Conf. Interval of the 95%]	
Ecuador	lnCO2_Intensity	1.023939	.0150136	68.20	0.000	.9945124	1.053365
	lnGVA	.4138185	.0236224	17.52	0.000	.3675195	.4601175
	GVA ²	-5.55e-16	1.51e-16	-3.69	0.000	-8.50e-16	-2.60e-16
	H2ORed	.4155469	.1389119	2.99	0.003	.1432845	.6878092
	_Cons	-10.08498	.366126	-27.55	0.000	-10.80257	-9.367383
	rho		.9791861	.0206487	47.42	0.000	.9387154
México	CO2_Intensity	8.91e-07	9.26e-08	9.63	0.000	7.10e-07	1.07e-06
	lnGVA	1.31483	.1679059	7.83	0.000	.9857409	1.64392
	GVA ²	-1.65e-10	2.09e-11	-7.90	0.000	-2.06e-10	-1.24e-10
	H2ORed	-1.799433	.277874	-6.48	0.000	-2.344056	-1.25481
	_Cons	-12.13185	1.702017	-7.13	0.000	-15.46774	-8.795961
	rho		.9671436	.0321469	30.09	0.000	.9041368

Note: With a significance level of 5%. p < 0,01, ** p < 0,05, * p < 0,1

In Ecuador, the positive and statistically significant coefficient of lnGVA, combined with the negative and significant coefficient of the squared term (GVA²), confirms the presence of a non-linear relationship between economic growth and carbon emissions. The estimated signs are consistent with the inverted-U hypothesis of the Environmental Kuznets Curve (EKC), implying that economic expansion initially intensifies environmental degradation but eventually leads to a decoupling process as income levels rise. From an economic standpoint, the negative quadratic term indicates diminishing marginal environmental pressure as productive structure and technology evolve. However, the curvature implied by the model suggests that the turning point lies at relatively high-income levels, meaning that Ecuador remains on the ascending segment of the EKC. This finding supports the argument that structural dependence on resource-intensive activities delays the environmental transition, as highlighted by Acheampong et al. (2021) and Schneider and Mellon-Bedi (2025).

To complement the sign-based EKC interpretation, we compute the implied turning point (i.e., the level of economic activity at which the effect of further growth on emissions changes from increasing to decreasing). Given the estimated EKC terms $\ln(GVA)$ and GVA^2 , the turning point is obtained as:

$$GVA^* = \sqrt{\frac{\beta_{\ln(GVA)}}{-2\beta_{(GVA)^2}}}$$

Using the SAR coefficients in Table 3, the implied turning point equals 19,308,274 for Ecuador and 63,122 for Mexico (in the same units used for GVA in the dataset). These values provide a direct quantitative benchmark to evaluate whether each country is still on the rising segment of the EKC or has moved beyond the turning phase.

The coefficient associated with access to drinking water (H2ORed) is positive and statistically significant, suggesting that improvements in service coverage are linked to higher carbon emissions. Rather than capturing a direct environmental effect, this variable reflects processes of urbanization and structural transformation that increase energy demand, infrastructure expansion, and productive activity, thereby intensifying environmental pressure in the absence of cleaner technologies. Furthermore, the spatial autoregressive parameter is positive and highly significant, indicating strong spatial dependence across provinces. This result reveals the existence of substantive spillover effects, whereby emissions in one territory are systematically influenced by those of neighboring regions. The presence of these spatial interactions supports the use of the SAR specification not only on statistical grounds but also from a theoretical perspective, as environmental externalities and productive structures tend to diffuse across contiguous areas.

In the case of Mexico, the positive and statistically significant coefficient of $\ln GVA$, together with the negative and highly significant coefficient of the squared term (GVA^2), confirms a non-linear relationship consistent with the inverted-U hypothesis of the Environmental Kuznets Curve. Compared to Ecuador, the estimated curvature suggests a more pronounced adjustment process, indicating that Mexico is positioned closer to—or already within—the declining segment of the EKC. From an economic perspective, this implies that further increases in income are associated with reductions in carbon emissions, reflecting structural transformation, technological upgrading, and greater regulatory capacity in more industrialized regions. These

findings align with Gómez and Rodríguez (2020) and Escamilla-García et al. (2024), who highlight the role of technological change and climate policy in accelerating the downward phase of the EKC.

An additional relevant finding is the negative and statistically significant coefficient of H2ORed, indicating that, unlike in Ecuador, greater access to basic infrastructure in Mexico is associated with lower carbon emissions. This result suggests that infrastructure expansion operates under higher efficiency standards, likely reflecting technological upgrading, improved urban planning, and stronger regulatory frameworks that mitigate environmental externalities. From an economic perspective, the negative association may capture the role of more advanced urban systems in reducing energy intensity and promoting cleaner production processes (Walle, 2020). Furthermore, the spatial autoregressive parameter is positive and statistically significant, confirming the presence of strong spatial autocorrelation in CO₂ emissions. This implies that environmental outcomes in one state are systematically influenced by those of neighboring regions, reinforcing the existence of regional spillovers and the importance of coordinated environmental policies.

3.3. Spatial Model Analysis SEM (Spatial Error Model)

Table 4 presents the results of the Spatial Error Model (SEM), which captures spatial effects through the error term. In this model, the Lambda parameter (λ) measures the spatial autocorrelation of the unobserved error. The results confirm a strong spatial dependence in both countries, which reinforces the need to incorporate regional structures in environmental analysis.

Table 4. Spatial Error Model (SEM) between Ecuador vs. Mexico

Country:	Variable:	Coefficient:	Standard Error:	Z-Value:	P value	[Conf. Interval of the 95%]	
Ecuador	lnCO2_Intensity	.9782677	.0168036	58.22	0.000	.9453332	1.011202
	lnGVA	.356615	.025516	13.98	0.000	.3066046	.4066254
	GVA ²	-4.19e-16	1.61e-16	-2.60	0.009	-7.36e-16	-1.03e-16
	H2ORed	.4953906	.1601639	3.09	0.002	.1814752	.8093061
	_Cons	-3.244387	.6617473	-4.90	0.000	-4.541388	-1.947386
	Lambda		.9157214	.0841231	10.89	0.000	.7508432
México	CO2_Intensity	8.54e-07	9.49e-08	9.00	0.000	6.68e-07	1.04e-06
	lnGVA	1.34322	.1639544	8.19	0.000	1.021883	1.664573
	GVA ²	-1.70e-10	2.10e-11	-8.10	0.000	-2.11e-10	-1.29e-10
	H2ORed	-1.675351	.2790382	-6.00	0.000	-2.222255	-1.128446
	Cons	-8.601354	4.232454	-2.03	0.042	-16.89681	-.3058964
	Lambda		.9718941	.0279994	34.71	0.000	.9170163

Note: With a significance level del 5%. p < 0,01, ** p < 0,05, * p < 0,1

In Ecuador, the positive sign of lnGVA together with the negative and statistically significant sign of GVA² reveals a concave relationship consistent with the initial stage of an Environmental Kuznets Curve. Rather than

describing background conditions, the model results indicate that economic activity is still associated with increasing environmental pressure, although the negative quadratic component suggests the emergence of a moderating effect at higher income levels. From a spatial perspective, this pattern implies that the structural transformation required for environmental improvement has not yet materialized uniformly across regions. Consequently, the EKC should be interpreted as incipient and not yet validated in its mature phase. This interpretation aligns with Zafar et al. (2019) and Usman et al. (2022), who argue that in fossil-fuel-dependent economies with limited environmental governance, the upward segment of the EKC tends to persist for longer periods.

Applying the same turning-point calculation to the SEM estimates confirms the nonlinear EKC implications. Based on the coefficients in Table 4 and the expression:

$$GVA^* = \frac{\beta_{\ln(GVA)}}{\sqrt{-2\beta_{(GVA)^2}}}$$

the implied turning point equals 20,628,982 for Ecuador and 62,854 for Mexico (in the same units used for GVA in the dataset). Overall, the turning-point values are very similar across SAR and SEM, which strengthens the robustness of the estimated nonlinear relationship.

The positive and statistically significant sign of H2ORed indicates that the expansion of basic infrastructure is associated with higher environmental pressure, suggesting that improvements in service coverage are occurring alongside increases in energy use and emissions. This result points to a scale effect that continues to dominate over potential efficiency gains, particularly in regions where infrastructure growth is not yet accompanied by cleaner technologies. Moreover, the high and significant lambda parameter reveals strong spatial dependence in the error term, implying that unobserved factors with a territorial dimension are influencing environmental outcomes. This pattern highlights the presence of spatial spillovers and suggests that the model captures only part of the regional dynamics, reinforcing the need to interpret the EKC within a spatially interconnected context.

In Mexico, the estimated signs reinforce the presence of a more advanced stage of the Environmental Kuznets Curve. The positive effect of lnGVA combined with the negative and highly significant quadratic term indicates a steeper concave pattern, suggesting that the economy is moving closer to the turning phase of the

EKC. Rather than reflecting background conditions, the results point to a context in which structural change and environmental management may be beginning to offset the scale effect of growth. This interpretation is consistent with Dogan et al. (2020), who emphasize that active environmental policies and more diversified productive structures can accelerate the transition toward the declining segment of the EKC.

Additionally, the negative sign of H2ORed suggests that the expansion of basic services is associated with efficiency gains or stricter environmental standards that help mitigate environmental pressure. This pattern contrasts with less efficient infrastructure expansions and is in line with Medina-Rivas et al. (2022). Finally, the high and statistically significant lambda parameter confirms the persistence of spatial dependence in CO₂ emissions, indicating that unobserved territorial factors and regional spillovers continue to shape environmental outcomes beyond the variables included in the model.

3.4. Comparative analysis of SAR and SEM Space Models

The comparison between the SAR and SEM spatial models for Ecuador and Mexico (Table 5) reveals notable differences in the spatial distribution of pollution, reflecting the structural heterogeneity of both economies in relation to the Environmental Kuznets Curve (EKC). Although the information criteria favor the SAR specification in both cases, the model selection is not based solely on goodness-of-fit measures. In Ecuador, the spatial autoregressive coefficient is positive and highly significant, indicating the presence of substantive spatial dependence whereby pollution levels in one province directly influence neighboring areas. This finding points to the existence of spillover effects rather than merely spatially correlated disturbances, thereby supporting the preference for the SAR model over the SEM specification. The lower residual dispersion and more favorable information criteria further reinforce the robustness of the SAR model. This pattern confirms that Ecuador's EKC remains in its ascending phase, where oil-related activities continue to generate persistent environmental pressures without reaching the turning point (Larrea and Warnars, 2009; Zafar et al., 2019).

Table 5. Comparison of SAR and SEM between Ecuador and Mexico

Country:	Model:	SAR (Modelo Autoregresivo Espacial):	SEM (Modelo de Error Espacial):
Ecuador	Probability of registration	-265.26353	-313.62024
	Varianza (Sigma)	0.44	0.50
	R ² (corr. square)	0.945	0.927
	Lambda (Bug Dependency)	-	.9157 (-3.626 < lambda < 1.000)
	Rho (Delay Unit)	.9791 (-3.626 < rho < 1.000)	-
	Test the Wald (Space Effect)	2248.772 (0.000)	118.494 (0.000)
	Likelihood ratio test	113.613 (0.000)	16.899 (0.000)
	Lagrange multiplier test	137.344 (0.000)	40.057 (0.000)

	AIC (Akaike Information Criteria)	542.5271	619.9926
	BIC (Bayesian Information Criterion)	566.9376	644.0602
	Probability of registration	-1337.0007	-1346.6644
	Varianza (Sigma)	2.45	2.49
	R ² (corr. square)	0.441	0.334
	Lambda (Bug Dependency)		.9718 (-3.385 < lambda < 1.000)
México	Rho (Delay Unit)	.9671 (-3.385 < rho < 1.000)	
	Test the Wald (Space Effect)	905.114 (0.000)	1204.871 (0.000)
	Likelihood ratio test	85.847 (0.000)	66.520 (0.000)
	Lagrange multiplier test	271.186 (0.000)	408.348 (0.000)
	AIC (Akaike Information Criteria)	2686.001	2705.329
	BIC (Bayesian Information Criterion)	2712.138	2731.465

Note: Own elaboration

The choice between the SAR and SEM specifications is supported by both statistical evidence and the underlying economic interpretation of spatial interaction. Statistically, Table 5 indicates that SAR provides better overall fit in both countries (higher R² and lower AIC/BIC), and the spatial parameters are highly significant, confirming that spatial dependence is a core feature of the data. In addition, the spatial dependence diagnostics reported in Table 2 justify the inclusion of a spatial structure. From a theoretical standpoint, SAR is appropriate when environmental outcomes propagate through direct inter-territorial spillovers, meaning that emissions in one province/state can influence neighboring territories through geographic and economic linkages. By contrast, SEM is more consistent with spatial dependence driven by spatially correlated unobserved shocks captured in the error term. Therefore, SAR is retained as the baseline specification for comparative interpretation of spillover effects, while SEM is reported as a complementary robustness specification.

From a methodological perspective, the results indicate that the SAR model provides a more robust specification than the SEM for both countries, although with differences in the intensity of spatial effects. In Ecuador, the spatial autoregressive coefficient is large and statistically significant, revealing strong regional interdependence whereby pollution spreads from major extractive hubs to neighboring areas. This pattern is consistent with the presence of substantive spatial spillovers rather than merely spatially correlated errors, which supports the appropriateness of the SAR specification. Such dynamics tend to prolong the ascending phase of the EKC by transmitting environmental pressures across adjacent territories. This evidence aligns with Jeetoo (2023), who highlights that economies characterized by concentrated productive structures and limited territorial planning often exhibit pollution processes that diffuse spatially. Under these conditions, spatial lag models such as SAR are better suited to capture distributed environmental externalities.

In Mexico, the SAR model also shows superior performance relative to the SEM in terms of overall fit and information criteria, although residual variability remains comparatively higher. The statistical significance of

both spatial parameters confirms the presence of regional interdependence; however, the magnitude and interpretation of the spatial lag coefficient suggest that spatial dependence operates mainly through interregional spillovers rather than through omitted spatial shocks. This indicates a more heterogeneous and less spatially uniform pattern of emissions compared to Ecuador. Such complexity reflects Mexico's broader territorial diversity and uneven industrial and urban development, consistent with the observations of Blackman et al. (2015) regarding the heterogeneous nature of environmental pressures in large and diverse national contexts.

The spatial distribution of pollution in Mexico is characterized by fragmentation across regions with differing levels of development and urbanization, revealing a spatial structure shaped by economic inequalities and differentiated urbanization processes (Chen et al., 2022). Similarly, Karahasan and Pinar (2022) demonstrate that regional productive heterogeneity generates complex environmental dispersion patterns, as also observed in the Mexican case. In this sense, the superior explanatory performance of the SAR model in both Mexico and Ecuador supports its usefulness as an analytical tool for examining environmental trajectories in developing economies (Herrera et al., 2024).

From a comparative standpoint, the findings indicate that the SAR model provides a more solid explanatory framework for both countries. In Ecuador, pollution is transmitted in a more direct and geographically dependent manner, reflecting a rigid EKC that remains in its ascending phase (Buenaño et al., 2023). In contrast, Mexico—due to its territorial scale and structural diversity—exhibits more dispersed and complex spatial patterns, with emissions fragmented across regions with varying degrees of industrialization and urban development (Medina-Rivas et al., 2022). This diversity complicates the representation of environmental dynamics through a single spatial specification, in line with the arguments of Percastre et al. (2024) regarding the role of economic and urban heterogeneity in shaping environmental pressures.

4. CONCLUSIONS

The environmental trajectories of Ecuador and Mexico reveal distinct paths within the framework of the Environmental Kuznets Curve (EKC), shaped by differences in productive structures and institutional capacities. While Ecuador remains in the ascending phase of the EKC, largely due to its dependence on extractive activities and the limited consolidation of environmental institutions, Mexico exhibits clearer evidence of having reached, or even surpassed, the turning point in certain regions. This divergence highlights how the nature of economic growth, whether resource-based or more industrialized and diversified, conditions

the potential for transitioning toward environmentally sustainable development pathways. The Mexican case illustrates that policies aimed at energy diversification and institutional strengthening can generate positive effects on emission reduction, although these efforts remain insufficient to achieve a homogeneous transition at the national scale.

The results further confirm that CO₂ emissions do not follow random patterns but are driven by significant spatial and territorial dynamics. In both countries, the spatial autocorrelation detected across all estimated models indicates that pollution processes are governed by shared regional logics. In Ecuador, emissions are concentrated in the Amazon and coastal regions, closely associated with oil extraction activities, whereas in Mexico, a more fragmented network of interconnected industrial hubs is observed. These findings validate the use of spatial econometric models as essential tools for capturing environmental externalities across contiguous territories and for designing differentiated mitigation policies tailored to regional characteristics.

The comparison between the SAR (Spatial Autoregressive Model) and SEM (Spatial Error Model) indicates that direct spatial interaction among regions, as captured by the SAR specification, exerts a stronger influence on emission patterns than unobserved residual spatial effects modeled by the SEM. This result highlights the importance of geographical contagion in shaping CO₂ emission processes. In Ecuador, the superior performance of the SAR model suggests that pollution in one province is closely linked to pollution in neighboring provinces, reflecting development patterns concentrated in extractive hubs. In Mexico, although the SAR model also performs better, the lower value of the spatial autoregressive parameter (ρ) and the higher residual variance reveal a more heterogeneous structure that is less dependent on immediate geographical proximity. Consequently, mitigation strategies should be adapted not only to the type of economy but also to the territorial configuration of each country: Ecuador requires targeted interventions in extractive clusters, whereas Mexico demands multi-level policies capable of addressing dispersed and diverse sources of pollution.

Access to basic services, such as piped water, exhibits contrasting effects across the two countries, indicating that its environmental impact depends critically on institutional context and the technological efficiency of infrastructure. In Ecuador, the expansion of public water networks is associated with higher emission levels, likely linked to rapid urban growth and increased energy demand in low-efficiency environments. By contrast, in Mexico, this variable exerts a negative effect on emissions, suggesting that efficient urban infrastructure and higher technological standards can contribute to reducing environmental

pressures. This contrast underscores the importance of complementing the expansion of basic service coverage with policies aimed at improving energy efficiency, promoting sustainable urban planning, and strengthening environmental regulation.

Finally, the dynamics of CO₂ emissions in both countries demonstrate that the Environmental Kuznets Curve hypothesis is neither automatic nor uniform. The transition toward sustainability requires more than economic growth alone; it depends on political commitment, sustained public investment, and strong institutions. Ecuador, despite recent advances, remains constrained by an extractivist model that perpetuates environmental degradation, while Mexico—although more advanced in relative terms—faces setbacks derived from policy decisions that weaken environmental governance and slow the expansion of clean energy. Consequently, EKC phases should be interpreted not as inevitable stages of development but as outcomes shaped by structural conditions and policy choices. This analysis highlights the urgency of rethinking growth strategies through an ecological and territorial lens, in which the State plays an active role in correcting externalities and leading a transition toward a genuinely sustainable development model.

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