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On the Latin America Evidence for the Environmental Kuznets Curve: A Two-Stage Approach using K-means Clustering and Polynomial Regression

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ABSTRACT

This paper uses a two-stage methodological approach to analyze the existence and shape of the Environmental Kuznets Curve (EKC) hypothesis across 19 Latin American countries from 2000 to 2020. First, K-means clustering is used to categorize countries based on their economic development, environmental efficiency, energy sustainability and technical efficiency characteristics. This clustering reveals five distinct groups: transitioning economies, resource-dependent economies, industrial economies, early transition economies, and advanced economies. Subsequently, polynomial regressions are estimated within each cluster to analyze the specific EKC relationships. The results demonstrate significant heterogeneity in the growth-environmental relationship across clusters, with coefficients of determinations ranging from 0.20 to 0.94. While some countries exhibit traditional inverted U-shaped relationships, others show different patterns, including U-shaped and linear relationships. The turning points at which environmental degradation (CO_2 emissions) begins to decrease vary substantially, from 1,722 USD in Panama to 241,024 USD in Venezuela, in per capita terms, highlighting diverse development trajectories. The empirical findings obtained suggest that the EKC relationship in Latin America is more complex than traditionally assumed and varies significantly based on countries' development stages and structural characteristics. These results have important implications for environmental policy design, suggesting the need for cluster-specific approaches rather than one-size-fits-all solutions.

Keywords: Environmental Kuznets Curve, Latin American countries, K-means, Polynomial Regressions
JEL Classifications: O13, Q53, C38, O54

1. INTRODUCTION

The Environmental Kuznets Curve (EKC) hypothesis suggests an inverted U-shaped relationship between economic growth and environmental degradation. The EKC hypothesis theorizes that environmental deterioration initially increases with economic growth, but eventually decreases as countries reach higher development levels, reflecting environmental awareness, technological advancement, and more robust regulatory framework.

Following the research results of Grossman and Krueger (1991) focusing on the environmental impacts of economic growth in North America through an EKC approach, a more general analysis of the EKC hypothesis in the rest of America remains a pending task. This general analysis should consider grouping countries that share similar characteristics, which will improve understanding of the complex relationship between growth and environmental damage in Latin America. Indeed, the region's distinct characteristics, such as significant economic disparities, heavy reliance on natural resources, different institutional qualities, and diverse patterns of urbanization and industrialization, make it a challenging case study for exploring the relationship between growth and environmental impact. Additionally, the varied nature of Latin American economies, which range from early-stage transitioning to advanced industrial states, offers a rich context for understanding how different levels of development influence environmental outcomes.

Literature empirical evidence suggests that the growth-environment nexus may follow different trajectories across different regions and country-specific factors influencing the EKC relationship, including institutional quality, trade openness and technological capacity; see, for instance Pesaran (2007), Westerlund (2007), Dogan and Inglesi-Lotz (2020) and, Zafeiriou et al. (2024).

This study aims to analyze the existence and shape of the EKC across 19 Latin American countries from 2000 to 2020, using data from the World Development indicators. The research employs a two-stage methodological approach: first, applying K-means clustering to categorize countries based on their economic and environmental characteristics capturing non-linear relationships and identifying natural groupings in multidimensional data, and second, conducting polynomial regression analysis within each cluster to examine the specific EKC relationships.

The remainder of this paper is organized as follows: Section 2 presents the evidence and review of the EKC literature, focusing on theoretical developments and empirical evidence from different regions and Latin America; section 3 describes the methodological framework, including the clustering approach and polynomial regression analysis; section 4 presents the results and discussion, analyzing the distinct patterns observed across different country clusters; finally, section 5 concludes with policy implications and suggestions for future research.

2. A SHORT LITERATURE REVIEW

Modern studies have significantly contributed to the EKC hypothesis by employing diverse econometric techniques and expanding datasets, improving the understanding of the complex relationship between economic growth and environmental degradation. Early studies primarily employed basic panel regression techniques, cross-sectional dependency tests and second-generation panel unit root tests (Pesaran, 2007), panel cointegration techniques (Westerlund, 2007), non-linear estimation methods (Dogan and Inglesi-Lotz, 2020), and Bayesian inference techniques (Zafeiriou et al., 2024).

For instance, Bimonte and Stabile (2024) use ordinary least squares (OLS) regression with heteroscedasticity-robust standard errors to examine the relationship between protected areas and per capita GDP in European countries. Their findings challenge the traditional EKC hypothesis, suggesting an inverted EKC pattern, particularly in advanced economies, meaning that further economic growth could increase environmental degradation beyond certain development thresholds. Moreover, Abbas et al. (2023) apply a Bayesian Vector Autoregression (BVAR) in their methodology highlighting the advantages of combining forecasting techniques with econometric analysis, especially when dealing with limited time series data.

The geographical scope of EKC studies has expanded significantly, focusing on regional variations. In this sense, Dogan and Inglesi-Lotz (2020) examine various European countries using panel data methods. They found that the EKC hypothesis is valid only when considering overall GDP growth rather than the industrial share of GDP. On the other hand, Shahbaz et al. (2019) analyze the case of Vietnam through ARDL and VECM approaches and found no support for the traditional EKC hypothesis. Instead, they identified an N-shaped relationship. Likewise, Wang et al. (2024) conduct quantile a regression analysis across 214 countries, revealing significant variations in the EKC relationship based on development levels.

Nevertheless, empirical evidence regarding the EKC in Latin America has been mixed. For instance, Koengkan and Fuinhas (2020) examine the capacity of renewable energy consumption to reduce outdoor air pollution death rates, finding no clear evidence supporting the EKC hypothesis. Other authors suggest that there are crucial factors influencing Latin America's EKC relationship showing that the strength of institutions and governance significantly affects the turning point of the EKC, as in Lorente and Alvarez-Herranz (2016). Moreover, some investigations have demonstrated that international trade can either accelerate or delay the achievement of the EKC turning point, depending on the specific context and complementary policies; see Shahbaz et al. (2019). Likewise, adopting cleaner technologies and innovation capacity has been found to play a crucial role in determining the shape and timing of the EKC relationship according to Balsalobre-Lorente et al. (2022). Additionally, the transition to renewable energy sources has emerged as a significant factor in modifying the traditional EKC relationship as shown in Anwar et al. (2021).

The analysis of the EKC hypothesis in Latin America faces several methodological challenges, including data quality and availability limitations in some countries, the presence of significant structural breaks due to the region's economic and political history, cross-sectional dependence arising from high levels of economic integration, and substantial heterogeneity among countries that require careful consideration of country-specific effects. Applying K-means clustering in EKC analysis offers several methodological advantages for understanding the complex relationship between growth and environmental degradation. First, K-means clustering allows for identifying distinct developmental stages across countries, aligning with the suggestion in Grossman and Krueger (1991) that economies follow different environmental trajectories based on their development level. Second, the algorithm's ability to minimize within-cluster variance while maximizing between-cluster differences, following Hartigan and Wong (1979), is desirable for capturing the heterogeneous nature of EKC relationships across different economic groups.

Clustering approach with K-means addresses what identifies as a critical challenge in EKC analysis: The need to account for structural differences among economies at various development stages; see Stern (2004). Furthermore, clustering enables the identification of what Dinda (2004) mentions as "transition thresholds" points at which economies shift from one development pattern to another. The K-means methodology is also useful for capturing non-linear relationships and identifying natural groupings in multidimensional data. Finally, K-means is helpful when analyzing the simultaneous interaction of economic, environmental, and energy-related variables that characterize the EKC hypothesis according to Panayotou (2016).

3. METHODOLOGY: ENVIRONMENTAL KUZNETS CURVE ESTIMATION

This study analyzes a dataset of 19 Latin American countries from 2000 to 2020 to examine the existence and shape of EKC. The variables included in this analysis are GDP per capita, CO_2 emissions per capita (measured in kilograms in constant 2015 USD), the percentage of renewable energy consumption relative to total final energy consumption, and the energy intensity of primary energy (measured in Mega-Joules adjusted for the purchasing power parity in 2017). All data was sourced from the World Development Indicators powered by the World Bank.

The previous variables were selected based on their relevance to the EKC hypothesis. GDP per capita will be used as the indicator of economic growth and CO_2 emissions per capita as a proxy variable of the environment deterioration in the EKC framework.

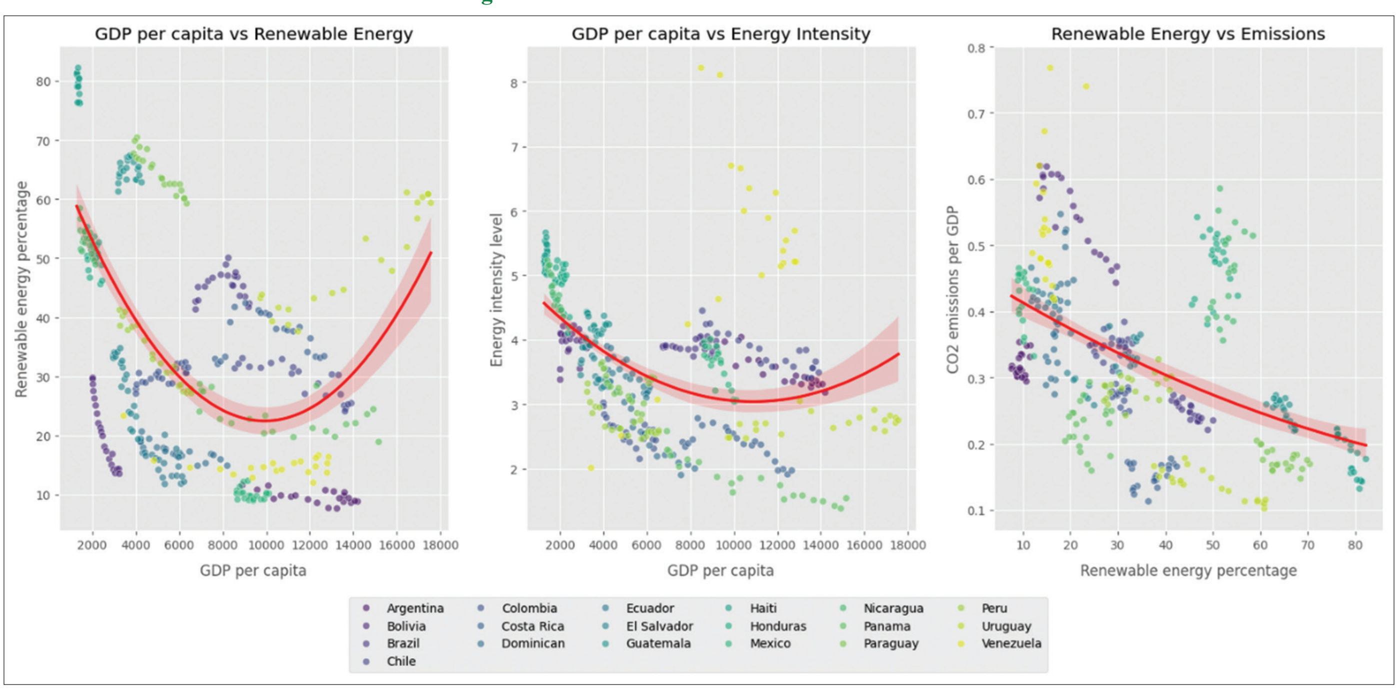
The percentage of renewable energy consumption represents the transition toward cleaner energy sources as economies develop, influencing the trajectory of ecological impact, as in Dinda (2004). Energy intensity indicates the efficiency of energy use in producing economic output. Improvements in this area are often linked to technological advancements and reduced environmental degradation; Stern (2004, p. 1420). Figure 1 shows the relationship among the proposed variables.

The first panel in Figure 1 shows the relationship between GDPs per capita and renewable energy consumption showing a distinctive U-shaped pattern, challenging conventional assumptions about development trajectories. At lower income levels (below 8,000 USD per capita), countries typically experience a decline in renewable energy usage as they transition from traditional biomass to fossil fuels. It is important to point out that the results in Wolfram et al. (2013) show this pattern in their study of developing economies. The curve reaches its lowest point at approximately 8,000 USD-10,000 USD per capita, indicating a crucial transition phase. Beyond this threshold, there is a clear upward trend in renewable energy adoption, especially in countries like Uruguay and Costa Rica. In this sense, the findings in Burke (2013) consider income thresholds' impact on clean energy transitions. This pattern aligns with what Carley et al. (2017) call the "energy ladder transition," in which countries initially move away from traditional renewable resources before investing in modern renewable technologies.

The second panel in Figure 1 shows the relationship between GDPs per capita and energy intensity negatively correlates with diminishing returns. This relationship features a steep decline in energy intensity at lower income levels (below 5,000 USD per capita), followed by a gradual flattening curve at higher income levels, with a slight upturn in the highest income brackets. This pattern strongly supports the findings in Stern (2017) on energy efficiency improvements in developing economies. It exemplifies what Filippini and Hunt (2011) describes as the "efficiency frontier" approach, where technological advancements and structural economic changes lead to improved energy utilization.

A particular finding is observed in the analysis of the percentage of renewable energy versus CO_2 emissions per GDP in the third panel of Figure 1, revealing a strong negative linear relationship. Countries with higher shares of renewable energy (exceeding 50%)

Figure 1: Environmental Kuznets curve variables



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consistently demonstrate lower emission intensities, with this relationship being most pronounced in the 20-60% renewable energy range. This inverse relationship provides robust empirical support for York and McGee (2017) findings on the emissions reduction potential of renewable energy adoption in developing countries. It must be highlighted that this pattern is evident in Costa Rica and Uruguay, which are regional examples of how integrating renewable energy can effectively reduce emission intensities.

All three previous relations significantly influence policy development and environmental management in Latin America. Critical intervention points arise, especially around the 8,000-10,000 USD per capita level, where countries may be best positioned to leapfrog to cleaner technologies. The findings also highlight regional characteristics that support and deviate from global EKC studies. In that sense, it is important to consider regional contexts in environmental policy design.

Now then, the EKC hypothesis suggests an inverted U-shaped relationship between economic development and environmental degradation. Hence, the basic theoretical model can be expressed as:

$$\ln \frac{E_{it}}{GDP_{it}} = \alpha_i + \beta_1 \ln\left(GDP_{it}\right) + \beta_2 \left[\ln\left(GDP_{it}\right)\right]^2 + \varepsilon_{it} \quad (1)$$

Where E_{it}/GDP_{it} it is environmental efficiency (for country i at time t) measured as CO_2 emissions per capita per unit of GDP per capita, GDP_{it} is the GDP per capita, α_i, β_1 and β_2 are parameters, and ε_{it} is the error term (white noise). From now on, for the sake of simplicity, we will refer to E_{it}/GDP_{it} as CO_2 emissions per capita. The quadratic term in equation (1) exhibits the hypothesis of a non-linear, inverted U-shaped relationship between economic growth per capita and CO_2 emissions per capita. The first term, $\beta_1 \ln(GDP_{it})$, captures the initial effect of economic growth on environmental degradation. In the early stages of economic development, as income per capita increases, environmental degradation typically rises due to industrialization, increased energy consumption, and limited environmental regulation. Finally, the second term, $\beta_2 [\ln(GDP_{it})]^2$, allows the model to account for a turning point. It introduces a non-linear relationship between economic growth and environmental degradation. As income grows beyond a certain threshold, economies often shift towards cleaner technologies, more efficient energy use, and stricter environmental regulations, reducing environmental degradation.

If $\beta_2 < 0$, then after reaching a certain level of GDP per capita, the positive relationship between economic growth and environmental degradation weakens and eventually turns negative. This turning point represents the threshold at which further economic growth leads to environmental improvements. The U-shape of EKC has three phases:

i. Left side of U-shape: Environmental degradation increases with economic growth due to industrialization and urbanization in low-income countries
ii. Turning point or peak of U-shape: This is the income level where the relationship changes from positive to negative
iii. Right side of U-Shape: In high-income countries, economic growth leads to environmental improvements through better technology, renewable energy, and more robust policies.

3.1. Stage 1: Clustering

This study follows a two-stage approach, beginning with cluster analysis and proceeding to polynomial regression. The initial clustering procedure serves as a foundational step, employing K-means methodology to categorize countries based on their multidimensional characteristics. This preliminary classification categorizes countries based on four key dimensions:

a) Economic growth (GDP per capita)
b) Environmental efficiency (CO_2 emissions per capita per unit of GDP per capita, or simply emissions per capita)
c) Energy sustainability (Renewable energy percentage)
d) Technical efficiency (Energy intensity level).

The clustering process follows Stern's (2004) methodology, standardizing variables to ensure comparability:

$$Z_{score} = \frac{x - \mu}{\sigma} \quad (2)$$

Subsequently, the K-means algorithm will be applied, which minimizes the objective function the within-cluster sum of squares (WCSS):

$$\text{WCSS} = \sum_{k=1}^{K} \sum_{x_i \in C_k} x_i - \mu_k{}^2 \quad (3)$$

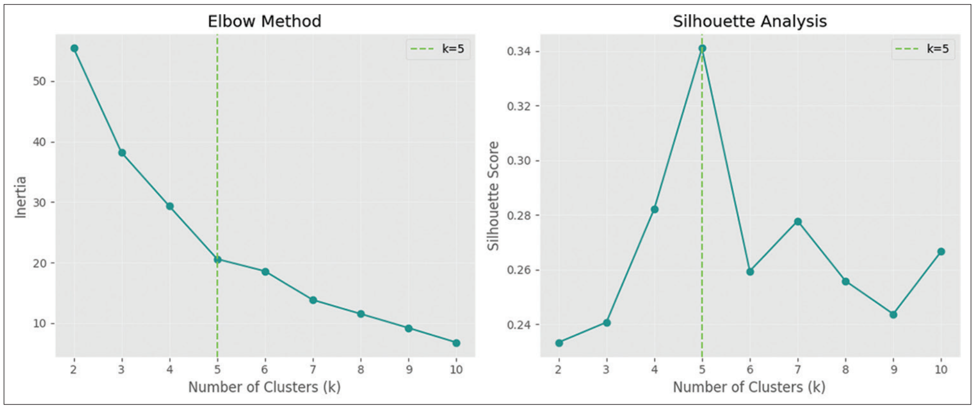
Where x_i represents the i-th observation, C_k is the k -th cluster, μ_k is the centroid of cluster k, and ‖•‖ is the Euclidean norm. As shown in Figure 2, WCSS is represented by the elbow curve that shows an inflection point at $k = 5$, where the reduction in inertia becomes markedly less pronounced (from 29 to 20), indicating that additional clusters beyond $k = 5$ provide diminishing returns in explaining data variability.

$$s\left(i\right) = \frac{b\left(i\right) - a\left(i\right)}{\max\left(a\left(i\right), b\left(i\right)\right)} \quad (4)$$

Elbow curve results are further corroborated by the silhouette analysis, which measures both cluster cohesion and separation. Here, $a(i)$ represents the mean intra-cluster distance and $b(i)$ the mean nearest-cluster distance for each observation i. The silhouette score reaches its maximum value of 0.34 at $k = 5$, indicating optimal cluster distinction and internal cohesion. This peak in the silhouette score, coupled with the elbow criterion, provides robust statistical support for the five-cluster solution. Both the elbow method and silhouette score, respectively, are represented in Figure 2.

Combining these two independent validation methods enhances the reliability of the clustering approach. Five clusters effectively capture Latin American countries' unique economic and environmental patterns. Using lower values for k would not adequately distinguish significant regional patterns, while higher values could lead to artificial distinctions not supported by the actual data structure. The results of the cluster analysis are presented in Table 1:

Figure 2: Optimal clusters and validation plots (Elbow and Silhouette)



Source: Authors' own elaboration

According to Table 1, the five distinct clusters are:
Cluster 0: Transitioning economies. This cluster includes Bolivia, Colombia, the Dominican Republic, Ecuador, El Salvador, and Peru. These countries have a moderate GDP per capita, averaging 4,570 USD, and relatively high CO_2 emissions at 0.37 kg per capita. The moderate share of renewable energy, at 24.2%, and the energy intensity of 3.16 indicate that these economies are moving towards more sustainable development paths.

Cluster 1: Resource-dependent economies. Guatemala, Haiti, and Paraguay form a unique group characterized by low GDP per capita, averaging 3,362 USD, and relatively low CO_2 emissions of 0.20 kg per capita. However, these countries have a high percentage of renewable energy sources, accounting for 69.4% of their energy mix. Their energy intensity is also notable at 4.26, indicating a heavy reliance on traditional biomass rather than modern renewable technologies.

Cluster 2: Industrial economies. Including Argentina, Brazil, Chile, Mexico, and Venezuela, these countries represent the region's industrial powerhouses, showcasing the second-highest average GDP per capita at 10,298 USD. However, they also have high CO_2 emissions, measured at 0.37 kg per capita. Furthermore, the low share of renewable energy, which stands at 21.8%, indicates a continued reliance on fossil fuels for industrial production.

Cluster 3: Early transition economies. Honduras and Nicaragua represent a region marked by low GDP per capita, approximately 1,926 USD, alongside high CO_2 emissions of 0.47 kg per capita. Despite these challenges, they have a significant share of renewable energy at 51.6% and a high energy intensity of 4.81. These factors indicate that these economies are in the early stages of industrial transition.

Cluster 4: Advanced Latin-American economies. Costa Rica, Panama, and Uruguay form the most economically advanced group in the region. They have the highest GDP per capita at 11,636 USD and the lowest CO_2 emissions at 0.17 kg per capita. Their moderate share of renewable energy stands at 36.6%, with a low energy intensity of 2.30. These figures indicate the successful implementation of efficient, clean technologies in these countries.

3.1.1. Emission by income group

Now that clustering has been stated, Figure 3 illustrates the distribution of CO_2 emissions per capita across various income groups, providing empirical evidence for the EKC hypothesis in Latin American economies. The boxplot analysis reveals distinct patterns of environmental degradation among five income categories identified through K-means clustering: transitioning economies, resource-dependent economies, industrial economies, early transition economies, and advanced Latin American economies. As before, CO_2 emissions are measured in kilograms per constant 2015 USD of GDP.

The boxplot analysis reveals significant variability in emission intensities. Early Transition Economies (Cluster 3) exhibit the highest median CO_2/GDP ratio, approximately 0.47 kg/GDP (variables in per capita terms), and the most extensive interquartile range. These observations align with Grossman and Krueger (1995) findings, which highlight the environmental challenges encountered by developing economies during their early stages of industrialization.

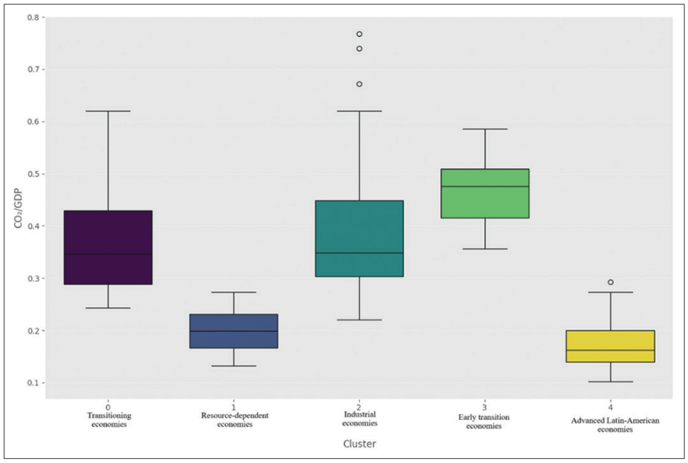
The advanced Latin American economies (Cluster 4) show the lowest median emissions at 0.17 kg of CO_2 per unit of GDP and have a notably compact interquartile range. This result supports the theoretical framework propose in Grossman and Krueger (1995), highlighting the environmental efficiency gains achieved by more developed economies. This trend aligns with the EKC hypothesis, suggesting that higher levels of economic development can lead to adopting cleaner technologies and implementing stricter environmental regulations, as in Stern (2017).

The outliers observed in the industrial economies (Cluster 2) extend beyond the whiskers, reaching approximately 0.77 kg/GDP. In this sense, Dinda (2004) suggests that these outliers are likely to indicate periods of intense industrial activity or specific economic shocks that temporarily increased emission intensities. In contrast, resource-dependent economies (Cluster 1) exhibit relatively low emissions despite their development stage, which may be attributed to their high share of renewable energy, a phenomenon documented

Table 1: Cluster analysis results (Authors' own elaboration)

Cluster	Size	Average GDP per capita	Average CO_2 emissions per GDP	Average renewable energy percentage	Average energy intensity level	Countries
0	6	4570.2326	0.3748	24.2872	3.1606	Bolivia, Colombia, Dominican, Ecuador, El Salvador, Peru
1	3	3362.4298	0.2019	69.4497	4.2613	Guatemala, Haiti, Paraguay
2	5	10,298.1374	0.3744	21.8295	4.0341	Argentina, Brazil, Chile, Mexico, Venezuela
3	2	1926.2542	0.4660	51.5798	4.8093	Honduras, Nicaragua
4	3	11,636.0721	0.1717	36.5898	2.2966	Costa Rica, Panama, Uruguay

Figure 3: CO_2 emissions by income group



Source: Authors' own elaboration

in studies by Panayotou (2016), which explores the relationship between energy composition and environmental performance in developing regions.

3.2. Stage 2: Polynomial Regression

In the second stage, a quadratic polynomial regression is estimated for each country within its respective cluster. For each country, the quadratic polynomial function is defined as:

$$\frac{CO2_{it}}{GDP_{it}} = \beta_0 + \beta_1 \frac{GDP_{it}}{P_{it}} + \beta_2 \frac{GDP_{it}}{P_{it}} + \varepsilon_{it} \quad (5)$$

Where β_0 represents the intercept term, β_1 captures the linear effect of GDP per capita, β_2 measures the quadratic effect, and ε is the error term. Since the variables are already standardized, it is not necessary to scale it into a logarithmic base. The model is estimated with ordinary least squares (OLS) after generating polynomial features through a second-degree transformation matrix. Finally, the turning point is calculated as:

$$TP = -\frac{\beta_1}{2\beta_2} \quad (6)$$

Which represents the GDP per capita level where environmental degradation begins to decrease. This turning point has significant policy implications: When $\beta_1 > 0$ and $\beta_2 < 0$, it confirms the inverted U-shape hypothesis and indicates the development threshold at which economic growth begins to support environmental improvement. The interpretation of the turning point varies across clusters, reflecting different development trajectories. For high-income clusters, the turning point often occurs at higher GDP levels, suggesting that environmental improvements require substantial economic development. In contrast, middle-income clusters might show earlier turning points, potentially indicating more efficient development paths or "tunneling through" the EKC; as in Munasinghe (1999). Table 2 shows the results of the quadratic polynomial regression:

The econometric analysis of the EKC across Latin American countries reveals significant differences in the relationship between economic growth and environmental degradation. The regression results show varying degrees of model fit, with R^2 values ranging from 0.085 for Ecuador to 0.938 for the Dominican Republic. This suggests that the EKC hypothesis is more applicable to some countries than others. Countries with R^2 values above 0.85 (such as the Dominican Republic, Venezuela, Bolivia, Colombia, Costa Rica, and Nicaragua) provide strong evidence supporting the environmental Kuznets relationship.

The turning points indicate the GDP per capita level at which environmental degradation begins to decline, showing significant variation across the region. The lowest turning points are found in Panama (1,722.15 USD), Honduras (2,002.71 USD), and Nicaragua (2,284.18 USD), suggesting that these countries may achieve environmental improvements at relatively lower income levels. In contrast, Venezuela has exceptionally high turning point of 241,023.99 USD may reflect structural challenges in adopting more environmentally efficient production methods. Most countries have turning points between 3,000 USD and 13,000 USD, consistent with previous research on developing economies (Stern, 2004). These turning points highlight the region's diverse development paths and environmental policy frameworks.

Likewise, the estimates of coefficients β_1 and β_2 typically demonstrate the expected pattern of an inverted U-shaped relationship, with several significant examples. For instance, the Dominican Republic exhibits a strong quadratic relationship β_2 = 1.403e−08 with a negative linear term β_1 = −0.00023, indicating a well-defined EKC pattern. Conversely, countries like Ecuador and Chile display weaker quadratic effects and lower R^2 values, suggesting that factors beyond the straightforward income-emissions link may explain their environmental and economic relationships more effectively. These observations align with Dasgupta et al. (2002) that noted that patterns of environmental improvement can vary considerably based on institutional strength and policy effectiveness rather than adhering to a uniform development trajectory.

Table 2: Polynomial regression results (sorted by R^2). Authors' own elaboration

Country	R^2	Turning Point	β_1	β_2	Cluster
Dominican	0.94	8129.48	−0.000228	1.40E-08	0
Venezuela	0.93	241,023.99	−0.000037	7.63E-11	2
Bolivia	0.88	2878.90	0.001139	−1.97E-07	0
Colombia	0.87	5897.71	−0.000309	2.62E-08	0
Costa Rica	0.87	7808.48	0.000034	−2.16E-09	4
Nicaragua	0.85	2284.18	−0.001145	2.51E-07	3
Paraguay	0.77	4901.24	−0.00021	2.14E-08	1
Uruguay	0.76	12,717.77	0.000062	−2.42E-09	4
Panama	0.72	1722.15	0.000002	−5.53E-10	4
Argentina	0.71	15,892.01	−0.000035	1.11E-09	2
El Salvador	0.56	2410.76	0.000155	−3.22E-08	0
Guatemala	0.52	3703.02	−0.000938	1.27E-07	1
Brazil	0.51	7930.17	−0.000296	1.87E-08	2
Mexico	0.51	8701.02	0.00075	−4.31E-08	2
Haiti	0.46	3206.05	0.000756	−1.18E-07	1
Honduras	0.44	2002.71	0.002116	−5.28E-07	3
Peru	0.29	7541.68	−0.000024	1.61E-09	0
Chile	0.20	12,445.36	−0.000029	1.17E-09	2
Ecuador	0.09	4692.77	0.000073	− 7.75E-09	0

4. RESULTS AND DISCUSSION

In this section, the EKC is presented for each country based on polynomial regression and clustered by K-means algorithm.

4.1. EKC for Transitioning Economies

Figure 4 illustrates diverse patterns among the countries studied: Bolivia, Colombia, the Dominican Republic, Ecuador, El Salvador, and Peru. The average GDP per capita is 4,570USD, and the average CO_2/GDP ratio stands at 0.375.

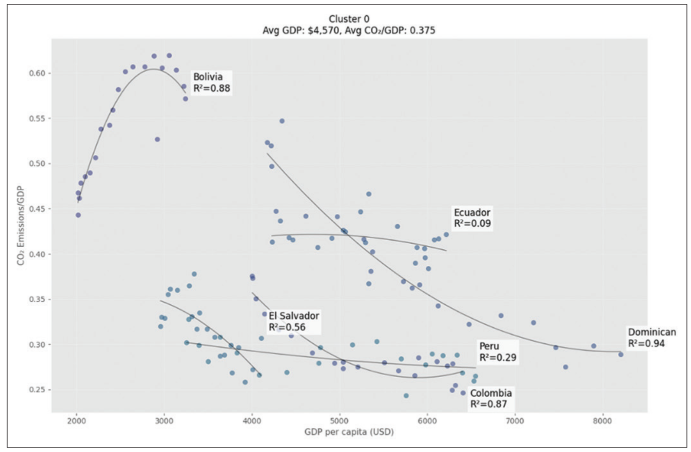
The most apparent evidence supporting the EKC hypothesis is observed in Bolivia, which has an R^2 value of 0.88. Bolivia shows an inverted U-shaped relationship between economic growth and environmental degradation, consistent with the findings of Grossman and Krueger (1995). The curve peaks at approximately 3,000 USD per capita, after which emissions decline, suggesting a critical transition in the country's development trajectory.

Colombia (R^2 = 0.87) and the Dominican Republic (R^2 = 0.94) also demonstrate strong statistical fits to the EKC model. However, their curves exhibit different inflection points and trajectories, supporting Stern (2004) argument that countries tend to follow distinct environmental-economic development paths.

In contrast, Ecuador (R^2 = 0.09) and Peru (R^2 = 0.29) show weaker relationships, challenging the EKC hypothesis's universal applicability. This divergence aligns with Dasgupta et al. (2002) "revised EKC" framework, suggesting that developing economies may experience different environmental trajectories based on their institutional capacities and policy frameworks. El Salvador (R^2 = 0.56) presents a moderate fit between these extremes, gradually decreasing emissions intensity as income rises.

This cluster's variation in turning points and curve shapes illustrates these countries' differing paths toward environmental sustainability. The Dominican Republic has the most apparent decline in emissions intensity at higher income levels, reinforcing the suggestions in Dinda (2004) regarding the impact of structural economic changes on environmental performance. Although these countries share similar levels of development, factors such as industrial structure, stringency of environmental policies, and technological adoption rates significantly influence their progress toward sustainability (Panayotou, 2016).

Figure 4: Kuznets curve for transitioning economies (cluster 0).



Source: Authors' own elaboration

This cluster indicates a gradual transition toward lower carbon intensity with increasing economic growth, though notable country-specific variations exist. Munasinghe (1999) argument about considering individual country contexts when designing environmental policies, even among seemingly similar economic groups.

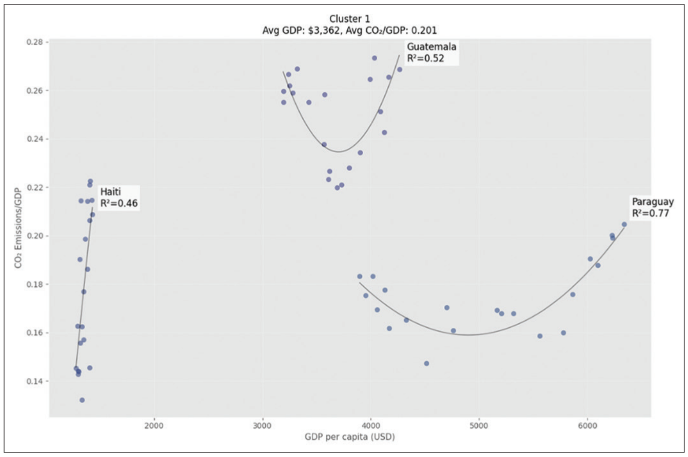
Finally, the strong EKC relationships observed in Bolivia, Colombia, and the Dominican Republic provide empirical support for the potential of achieving environmental improvements through economic development. In contrast, the weaker relationships in other countries highlight the need for targeted policy interventions to ensure that improvements in environmental quality accompany economic growth.

4.2. EKC for Resource-Dependent Economies

Analyzing the cluster 1 related to resource-dependent economies, it shows distinct patterns among Guatemala, Haiti, and Paraguay. This cluster has a low average GDP per capita of 3,362 USD and a relatively low average CO_2/GDP ratio of 0.201. These findings are illustrated in Figure 5.

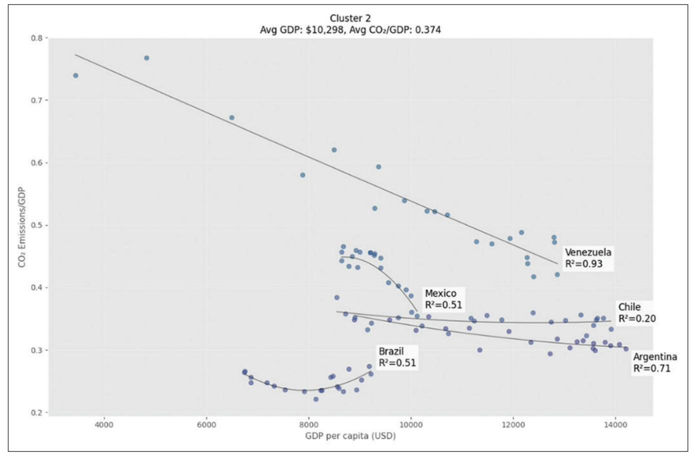
Paraguay demonstrates the most robust statistical alignment with the Environmental Kuznets Curve (EKC) model, with an R^2 value of 0.77. It exhibits a U-shaped curve instead of the expected inverted U relationship. This finding aligns with Arrow et al. (1995) that noted the complex relationship between economic growth and environmental quality in resource-dependent economies. The curve indicates an initial decline in emissions intensity up to a GDP per capita of approximately 4,500 USD, after which it begins to rise again. This pattern suggests what Kaika and Zervas (2013) call a potential "re-linking" phase between economic growth and environmental degradation.

Figure 5: Kuznets curve for resource-dependent economies (cluster 1)



Source: Authors' own elaboration

Figure 6: Kuznets curve for industrial economies (cluster 2)



Source: Authors' own elaboration

Guatemala ($R^2 = 0.52$) and Haiti ($R^2 = 0.46$) display moderate fits to the quadratic model but follow distinctly different trajectories. Guatemala's emissions intensity exhibits more significant variability across its GDP range, corresponding with Özokcu and Özdemir (2017) findings regarding the volatility of environmental performance in agriculture-based economies. In contrast, Haiti's trajectory starts from lower GDP levels, it shows a nearly linear increase in emissions intensity as economic growth occurs, supporting the arguments in Cole (2004) on the challenges faced by least-developed countries in balancing economic development with environmental protection.

An intriguing aspect of this cluster is the high average percentage of renewable energy (69.4%), accompanied by varying emission patterns. This observation aligns with updated analysis of the EKC in Stern (2017), which emphasizes that traditional renewable energy sources, such as biomass, may not necessarily lead to lower carbon intensities in developing economies. The overall pattern of this cluster suggests what Kander et al. (2017) describe as a "development trap," where resource-dependent economies struggle to achieve economic growth and environmental improvement without significant structural changes in their production systems.

Moreover, the differing patterns within this cluster support the arguments of Andreoni and Levinson (2001), that contend that the relationship between economic growth and environmental quality is fundamentally influenced by a country's technological capabilities and institutional frameworks rather than following a one-size-fits-all pattern. Despite lower income levels, the relatively low emission intensities compared to other clusters indicate unique developmental pathways that warrant further investigation for their potential contributions to sustainable development strategies in similar economies.

4.3. EKC for Industrial Economies

The results for Cluster 2 related to industrial economies presents intriguing patterns among Latin America's largest economies (Argentina, Brazil, Chile, Mexico, and Venezuela), characterized by the second-highest average GDP per capita (10,298 USD) and a relatively high average CO_2/GDP ratio of 0.374, as presented in Figure 6.

Venezuela demonstrates the strongest statistical fit ($R^2 = 0.93$), exhibiting a linear declining relationship rather than the expected EKC. This finding aligns with the conclusions in Perman and Stern (2003) that some resource-rich economies can reduce their emissions intensity as their economies grow. However, the high initial emissions level (approximately 0.77 kg CO_2/GDP) requires attention.

Argentina ($R^2 = 0.71$) displays a more conventional EKC pattern, supporting the results in Narayan and Narayan (2010) regarding the varying environmental-economic trajectories of middle-income industrialized countries.

Brazil and Mexico ($R^2 = 0.51$) show moderate fits to the EKC model, with relatively stable emissions intensities across their GDP ranges. This trend aligns with De Bruyn et al. (1998) that describe this phase as a "steady state" in industrial economies where technological advancements generally offset the environmental impacts of economic growth.

Chile's notably weaker fit ($R^2 = 0.20$) indicates potential influences from sector-specific factors and policy interventions that may disrupt the expected EKC relationship, as identified in Mazzanti and Musolesi (2013).

A distinctive aspect of this group is the divergence in emission intensities despite similar GDP levels. This variation supports the argument Richmond and Kaufmann (2006) that the interaction between economic growth and environmental degradation is significantly driven by energy prices and industrial structure rather than income levels alone. The overall pattern of this cluster suggests what Holtz-Eakin and Selden (1995) describes as a "plateau effect" where emissions intensity stabilizes at higher income levels but does not necessarily decline significantly.

The diverse trajectories within this industrialized cluster highlight the conclusions in Wagner (2008) regarding the significance of country-specific technological capabilities and environmental policies in shaping environmental outcomes. These findings imply that even among similarly industrialized economies, the path to environmental sustainability may require shaped approaches considering each country's unique economic structure and environmental challenges.

4.4. EKC for Early Transition Economies

Continuing with the EKC for Cluster 3, which includes early transition economies such as Honduras and Nicaragua. It is noted that distinct patterns at the lower end of the economic development spectrum. This cluster has the lowest average GDP per capita at 1,926 USD and the highest average CO_2 per GDP ratio at 0.466. These findings are illustrated in Figure 7.

Nicaragua exhibits a statistically solid correlation ($R^2 = 0.85$) with a clear downward trend in emissions intensity as GDP increases, challenging the traditional EKC hypothesis, which usually predicts rising emissions during the early stages of development. This trend aligns with the idea of Unruh and Moomaw (1998) regarding "tunneling through" the EKC, suggesting that some developing economies can skip the high-pollution phase of development. The significant decline in emissions intensity (from approximately 0.58-0.38 kg CO_2 per GDP) over a relatively narrow GDP per capita range (1,400 USD-2,000 USD) supports the findings of Bhattarai and Hamming (2001), which highlight the potential for rapid environmental improvements in early-stage economies.

In contrast, Honduras shows a weaker correlation ($R^2 = 0.44$) with a more volatile pattern and more significant variability in emissions intensity across its GDP range. This inconsistent pattern aligns with Suri and Chapman (1998) description of "developmental volatility," characteristic of economies in early transition phases, where structural changes and external shocks can significantly affect environmental performance. Honduras's emissions trajectory, which includes increases and decreases, supports the argument in Torras and Boyce (1998) regarding the importance of institutional factors in shaping environmental outcomes during early development stages.

A notable aspect of this comparison is the contrasting patterns between the two countries despite their similar income levels and geographic proximity. This divergence is consistent with the revised EKC framework in Dasgupta et al. (2002), which emphasizes that developing countries may follow different environmental paths based on their policy choices and institutional capabilities. The cluster's overall high emissions intensity about GDP reflects Panayotou (2016) findings on the environmental challenges faced by economies in the early stages of industrialization. Meanwhile, Nicaragua's potential for emissions reduction illustrates the significance of technological leapfrogging in achieving environmental improvements at lower income levels, as noted by Stern et al. (1996).

The differing experiences of Honduras and Nicaragua within this cluster highlight the conclusions on the critical role of policy frameworks and institutional capacity in determining environmental outcomes during early development stages (Yandle et al., 2004). These findings suggest that the journey toward environmental sustainability can vary significantly among countries at similar development levels, primarily influenced by domestic policy choices and institutional arrangements.

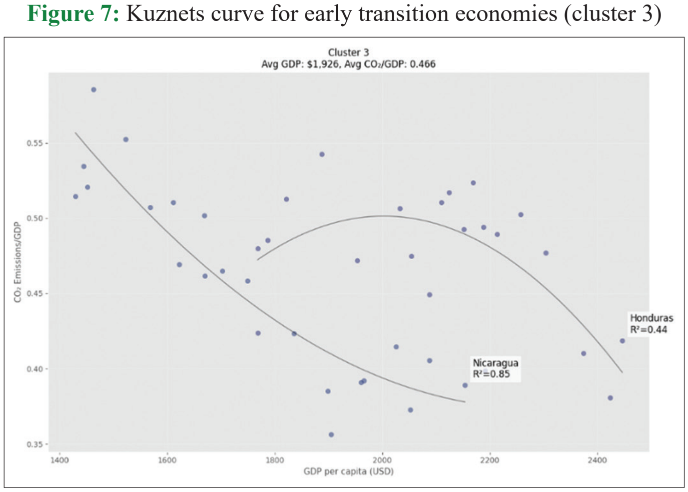
4.5. EKC for Advanced Latin-American Economies

Finally, the EKC for Cluster 4 which is related to advanced Latin-American economies reveals sophisticated environmental-economic relationships among Costa Rica, Panama, and Uruguay, characterized by the highest average GDP per capita (11,636 USD) and notably the lowest average CO_2/GDP ratio (0.172) across all clusters as exhibit in Figure 8.

Costa Rica exhibits the most robust statistical fit ($R^2 = 0.87$) with a distinct downward curve, illustrating what Jänicke et al. (1997), refer to as "environmental efficiency gains" in advanced economies. The country demonstrates continuous improvements in emissions intensity even at higher income levels, supporting the hypothesis by Porter and Van der Linde (1995) that environmental regulation and economic competitiveness can mutually reinforce one another in well-structured economies.

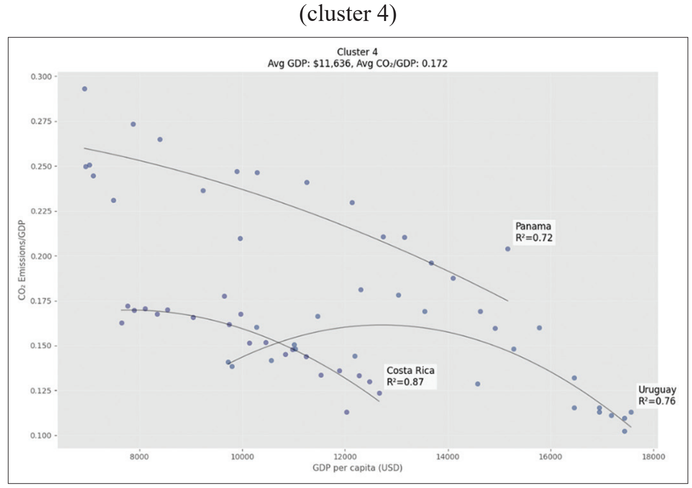
Panama ($R^2 = 0.72$) and Uruguay ($R^2 = 0.76$) also show robust fits to the EKC, though with varying trajectories. Panama's curve reveals a steeper decline in emissions intensity at higher GDP levels, which aligns with the findings Vukina et al. (1999) on the

Figure 7: Kuznets curve for early transition economies (cluster 3)



Source: Authors' own elaboration

Figure 8: Kuznets curve for Advanced Latin-American economies (cluster 4)



Source: Authors' own elaboration

accelerated environmental improvements possible in service-oriented economies. Conversely, Uruguay's pattern reflects what Shafik (1992) identify as a "mature economy" response, where environmental improvements persist even at higher income levels, although at a more gradual pace.

A notable characteristic of this cluster is the consistently low emissions intensity among all three countries, ranging from approximately 0.10-0.30 kg CO_2/GD. In this sense, Lopez and Mitra (2000) arguments regard the role of good governance and effective environmental policy in achieving sustainable development. The overall pattern of this cluster aligns with Copeland and Taylor (2004) concept of the "technique effect," which suggests that technological advancement and policy maturity lead to sustained environmental improvements.

The convergence of environmental performance among these countries at higher income levels, particularly above 15,000 USD per capita, is in line with the conclusions in Barrett and Graddy (2000) about the significance of institutional quality in environmental outcomes. These findings indicate that advanced Latin American economies have successfully adopted what Mol (2000) calls "ecological modernization," where economic growth becomes increasingly decoupled from environmental degradation through technological innovation and sophisticated policy measures.

5. CONCLUSION

The present study aimed to analyze the existence and shape of the Environmental Kuznets Curve across 19 Latin American countries from 2000 to 2020, employing a two-stage methodological approach that combines K-means clustering with polynomial regression analysis. This research is relevant given Latin America's characteristics, including significant economic disparities, heavy reliance on natural resources, varying institutional qualities, and diverse urbanization and industrialization patterns.

The clustering analysis revealed five distinct groups of countries with varying development and environmental patterns: Transitioning economies, resource-dependent economies, industrial economies, early transition economies, and advanced Latin American economies. The classification estimated with K-means indicates how different development stages influence the relationship between economic growth and environmental degradation, moving beyond the traditional one-size-fits-all approach to EKC analysis.

The empirical findings obtained demonstrate significant heterogeneity in the growth-environment relationship across Latin American countries. The polynomial regression results show R^2 values ranging from 0.20 to 0.94, with turning points varying substantially from 1,722 USD in Panama to 241,024 USD in Venezuela. While some countries exhibit the traditional inverted U-shaped relationship (e.g., Bolivia, Colombia, and the Dominican Republic), others show different patterns, including U-shaped curves (Paraguay) and linear relationships (Venezuela). This heterogeneity suggests that the EKC relationship is more complex than traditionally assumed and varies significantly based on countries' development stages and structural characteristics.

Likewise, the empirical findings obtained align with and extend several key studies in EKC literature. The heterogeneous patterns observed support the "revised EKC" framework in Dasgupta et al. (2002), which suggests that developing economies may follow different environmental trajectories based on their institutional capacities. The varying turning points across clusters reinforce the argument of Stern (2004) on the importance of considering structural differences among economies at different development stages. Furthermore, the findings regarding advanced Latin American economies, particularly Costa Rica and Uruguay, Porter and Van der Linde (1995) hypothesis that environmental regulation and economic competitiveness can be mutually reinforcing in well-structured economies. The case of resource-dependent economies in the present study aligns with the results in Kaika and Zervas (2013) regarding the potential "re-linking" phase between economic growth and environmental degradation, particularly evident in Paraguay's U-shaped curve pattern.

Several limitations and opportunities for future research emerge from this study. First, the present analysis focused on CO_2 emissions as the primary environmental indicator; future studies could incorporate additional environmental variables (nitrous oxide and methane) to provide a more comprehensive picture of environmental degradation. Second, while the clustering approach captured economic and ecological characteristics, future research could include institutional variables and policy indicators to better understand their role in shaping the EKC relationship. Finally, the analysis can be extended to include longer series and incorporate the impact of external shocks (such as economic crises or policy changes), which could provide an interesting view of the dynamic nature of the growth-environment relationship.

The present research contributes to existing literature in several ways. First, it introduces a methodological approach that combines clustering and polynomial regression to capture the heterogeneity in EKC relationships. Second, it provides empirical evidence that challenges the universal applicability of the traditional EKC hypothesis in Latin America. Finally, it highlights the importance of considering country-specific characteristics and development stages when designing environmental policies. Differentiated approaches may be more effective than uniform policy prescriptions for achieving regional environmental sustainability, which suggests the need for cluster-specific approaches rather than one-size-fits-all solutions.

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