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RESEARCH

Perspectives on the environmental Kuznets curve in America: a static panel approach for the period 2010-2020

Perspectivas sobre la curva de Kuznets ambiental en America: un enfoque de panel estático para el período 2010-2020

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Abstract

This study aims to determine the relationship between economic growth and CO_2 emissions through the hypothesis of the Environmental Kuznets Curve for 25 countries of the American continent covering the period 2010-2020. The methodology used is a panel data model that employs a static panel regression with cluster, measuring CO_2 emissions and their relationship with the variables GDP per capita, electricity consumption, income from environmental taxes, exports, and imports in America. The result of the model allows for visualization of an inverted U-shaped association between environmental degradation and the variables considered, the estimates have the expected signs and are statistically significant, resulting in empirical support for the presence of a hypothesis of the Environmental Kuznets Curve, evidencing the need to implement public policies that promote environmental care.

Keywords: economic growth, CO_2 emissions, Environmental Kuznets Curve, American continent, panel data.

Code JEL: Q38, Q50, Q51, Q56

Resumen

El objetivo del presente estudio es determinar la relación entre crecimiento económico y emisiones de CO_2, a través de la hipótesis de la Curva de Kuznets Ambiental, para 25 países del continente americano que abarca el período 2010–2020. La metodología utilizada es un modelo con datos de panel que emplea una regresión de panel estático con clúster, midiendo las emisiones de CO_2 y su relación con las variables PIB per cápita, consumo de energía eléctrica, ingresos por impuestos ambientales, exportaciones e importaciones en América. El resultado del modelo permite visualizar una asociación en forma de U invertida entre la degradación ambiental y las variables consideradas, las estimaciones tienen los signos esperados y son estadísticamente significativas, dando como resultado apoyo empírico a la presencia de una hipótesis de la Curva Ambiental de Kuznets, evidenciando la necesidad de implementación de políticas públicas que fomenten el cuidado del medio ambiente.

Palabras clave: crecimiento económico, emisiones CO_2, Curva Ambiental de Kuznets, continente americano, datos panel.

Código JEL: Q38, Q50, Q51, Q56

1. Introduction

Climate change and environmental degradation are global challenges that require a deep understanding of how economic development impacts the environment (Chen et al., 2024; Naseem et al., 2024; Magazzino et al., 2023). The Environmental Kuznets Curve offers one of the best-known theoretical perspectives to address this issue and demonstrates the relationship between economic growth and greenhouse gas emissions (Azimi & Bian, 2023; Chu, 2021; Fang et al., 2019).

Governments and international organizations are now taking stronger measures to combat climate change and promote sustainability as rising temperatures, melting glaciers, rising sea levels, extreme weather events, and changing precipitation patterns are increasingly evident around the world (Adebayo et al., 2022; Adedoyin et al., 2021; Ahmad et al., 2017).

Therefore, it is crucial to identify the key variables that influence per capita emissions so that the results of this study can significantly inform the formulation of effective environmental policies. The objective is to verify whether the Environmental Kuznets Curve (EKC) is fulfilled in America from 2010 to 2020 through an econometric model with panel data that allows the identification of some variables that are related to CO_2 emissions and thus determine whether the EKC is fulfilled for America in the last decade.

Using a static panel data econometric model is an advanced and robust methodology for analyzing a large amount of data over an extended period. This methodology can provide accurate and reliable results.

It was determined that it was important to analyze America because, despite the extensive literature on the Kuznets curve worldwide, there is a need for more specific studies investigating its applicability in America during the last decade. This study seeks to fill this gap and provide a more detailed view of the relationship between growth and the environment in the region. At the same time, it is possible to determine the level of correlation between per capita emissions and per capita GDP in the countries of America during the period 2010-2020, the variables that have had the greatest impact on the generation of emissions.

The article is organized as follows: The next section reviews the literature of the most representative research that relates the variables of economic growth and CO_2 emissions, emphasizing the methodologies used. Subsequently, the methodology and data used in this study are described. Finally, a discussion and conclusion of the findings obtained are presented.

2. Literature Review

Several investigations analyze the relationship between economic growth, energy consumption, and environmental pollutants, from two perspectives (Apergis & Ozturk, 2015; Bekun et al., 2023). The first focuses on environmental pollutants and their link with growth, which are closely related to testing the validity of the Environmental Kuznets Curve (EKC) hypothesis, which postulates that environmental degradation increases during the early stages of economic growth and then decreases with per capita income after reaching a threshold (Bao & Lu, 2023; Alsaedi et al., 2022; Gill et al., 2018; Grossman & Krueger, 1995). Results of these studies reveal that there is an inconsistent association between CO_2 emissions and growth because there are other factors that largely depend on specific dynamics at the regional and national levels (Fakher et al., 2023; Massagony & Budiono, 2022; Cetin et al., 2022).

The second perspective supports evidence of causality between energy consumption and economic growth; the association of the two variables is related depending on the data set, the specification model, and the econometric technique involved (Bulut, 2019; Balsalobre-Lorente et al., 2022). In this sense, higher energy consumption to achieve a rapid pace of economic growth causes significant degradation of environmental quality (Çobanoğulları, 2024; Ramzan et al., 2022; Wang & Jiang, 2020). That is, economic growth is characterized by urbanization, industrialization, and improvement of transportation infrastructure, causing a higher level of energy consumption and ultimately carbon emissions compounds (Pradhan et al., 2024; Ullah et al., 2022; Yang et al., 2015).

2.1. Economic growth and CO_2 emissions

Society tends to demand a healthy and sustainable environment as its income levels increase; these aspirations can be achieved if there are technological improvements or if governments impose stricter environmental controls (Zuhal & Göcen, 2024; Nawapanan et al., 2022; Kan et al., 2019). Currently, global economic growth has led to the generation of air pollutants caused by human activities such as deforestation, the change in land use to convert it into land for livestock or agriculture, electricity production, and the use of motor vehicles. Consequently, the expansion of economic activity and pollutant emissions tend to grow (Barut et al., 2023; Sun et al., 2021; Vadén et al., 2020).

Global CO2 emissions come mainly from several key industrial sectors (Mehmood et al., 2024; Zuhal & Göcen, 2024). The transport industry, which includes maritime cargo transport, is responsible for a significant share of emissions, due to the use of fossil fuels in ships and cargo vehicles (Awan et al., 2022). Commercial aviation also contributes significantly, with aircraft being one of the main sources of greenhouse gas emissions in the transport sector. In addition, the automotive industry, driven by the mass consumption of motor vehicles, represents another important source of CO2 emissions (Leal Filho et al., 2023; Li et al., 2023). Industrial production and energy generation from fossil fuels are also large emitters, consolidating themselves as key sectors in the fight against climate change. Other sectors, such as agriculture and construction, also play an important role, but to a lesser extent compared to those mentioned (Fakher et al., 2023; Qin et al., 2024). A sectoral understanding of emissions is crucial to developing effective mitigation strategies.

In particular, CO_2 emissions are considered to have the greatest participation in the greenhouse effect in the Earth's atmosphere and are considered the main cause of global warming. Therefore, these types of emissions in a country are an indicator of how it influences climate change (Li et al., 2016; Wang & Jiang, 2019; Huh, 2020).

Thus, Abid (2015) supports the relationship between economic growth and carbon emissions in the presence of the informal economy in Tunisia from 1980 to 2009; as a result, he obtained unidirectional causality from formal economic growth to CO_2 emissions, while bidirectional causality was demonstrated between CO_2 emissions and GDP.

For their part, Lv et al. (2019) investigate the impact on the short- and long-term equilibrium of the dynamic causality relationships between economic growth, CO_2 emissions, and fossil fuel consumption in China between 1965 and 2016; using econometric techniques (cointegration and linear and non-linear Granger causality in multivariate settings) they found that emissions not only lead to immediate economic growth, but also to future economic growth, both linear and non-linear. That is, greenhouse gas emissions and/or fossil fuel consumption do not lead to a slowdown in economic growth in China.

The study by Khan et al. (2022) supports a progressive correlation between carbon emissions, economic growth, and the use of energy and oil in 18 countries among the 20 main contributors to the tourism sector in the period from 1995 to 2019. The regression technique used shows that economic growth has a negative impact on environmental degradation. Therefore, in their quest to achieve stable and lasting tourism in the countries studied, the authors consider, as a first step, educating society to use public transport and other alternative fuels such as advanced hybrid technologies.

2.2. Environmental Kuznets Curve

The literature review allows us to identify that the most well-known assumption for investigating the possible detrimental impacts of economic growth on environmental quality is the Environmental Kuznets Curve (EKC) hypothesis. The main theoretical framework of the EKC hypothesis is inspired by the original idea of Simon Kuznets (1955), who stated an inverted U-shaped relationship between income inequality and economic growth; he stated that income inequality increases and reaches its maximum point in the initial phase of development. However, he stated that after that point, economic development and income inequality improved with economic growth.

Thus, the Environmental Kuznets Curve (EKC) proposes an inverted "U" relationship between economic growth and environmental degradation, which has been tested in different contexts and with different methodologies. For example, Adebayo et al. (2022) evaluate the effect of economic complexity on CO_2 emissions in Mexico, Indonesia, Nigeria, and Turkey (a group of countries called MINT economies), considering the role of financial development, economic growth, and energy consumption for the period between 1990 and 2018. The authors use the quantile moments regression method with fixed effects, which allows them to find that there is an inverted U-shaped interrelationship between economic growth and CO_2 emissions, thus validating the EKC hypothesis.

Wang, Yang, and Li (2023) set income inequality as the threshold variable, economic growth as the explanatory variable, and carbon emission as the explained variable, and the threshold panel model is developed using data from 56 countries. The empirical results show that income inequality has changed the relationship between economic growth and carbon emissions from an inverted U-shape to an N-shape, which means that income inequality redefines the environmental Kuznets curve and increases the complexity of the decoupling of economic growth and carbon emissions.

At the frontier of knowledge, there are a variety of empirical studies related to EKC in the American continent, both for developed countries as well as developing countries. Table 1 shows some research on the EKC, which studies the relationship between economic growth and CO_2 emissions, most of them refer to groups of countries (Pinilla-Rivera et al., 2018; Ortiz-Paniagua & Gómez, 2021; Zeraibi et al., 2023) and, to a lesser extent, those studies that show a single country or city (Bulut, 2019; Haider et al., 2022; Acevedo-Ramos et al., 2023).

Mainly, from the perspective of the methodology used, some studies from a multivariate framework use the Generalized Method of Moments(GMM) methodology (Taghvaee et al., 2022; Wang et al., 2023a), while others use both parametric and semiparametric additive models like Ordinary Least Square (OLS) regressions (Arango-Mirando et al., 2020; Bekun et al., 2021; Magazzino et al., 2023) and Autoregressive Distributed Lag (ARDL) stationarity models to analyze dynamic relationships with time series data in a single-equation (Haider et al., 2022; Çobanoğulları, 2024).

3. Methodology

3.1 Model specification

For this study, an econometric approach was used. This approach involved analyzing panel data from a sample of 25 American nations from 2010 to 2020. This approach consisted of creating a panel linear regression model, where clusters in the residuals were considered in geographic and temporal terms.

3.2. Model variables

A model was proposed considering endogenous variables such as the per capita emissions of 25 countries from 2010 to 2020 and exogenous variables such as GDP per capita, electricity consumption, tax revenues, and imports/exports as a percentage of GDP. This choice is based on the fact that these variables are widely used to calculate environmental degradation. This selection aligns with established methodologies, as variables like GDP per capita and per capita emissions are standard metrics in environmental-economic analyses, ensuring comparability and reliability in assessing environmental degradation.

The final formulation of the model is presented below:

$$PC\ emissions = f\,(GDPCC_{it}, GWh_{it}, IPI\ it, I/E\ GDP_{it},) + \alpha_i + \varepsilon_i \quad \text{[Eq.1]}$$

Where:

PC emissions = emissions per capita

GDPPC = Gross Domestic Product per capita

GWh = electricity consumption

IPI= tax revenues

I/E GDP = imports/exports about GDP

i = country

t= year

3.3. Signs and magnitudes of the parameters

Below is Table 2, which compiles the model's variables, including their nomenclature, meaning, and expected sign.

3.4. Model estimation

3.4.1. Data collection for model estimation

Panel data were used to carry out the model prediction, which amalgamated temporal and

Table 1. Previous studies validating/invalidating the EKC Hypothesis for America

Article	Period	Countries	Method	Dependent Variable	Explanatory Variables	EKC Hypothesis
Pinilla-Rivera et al. (2018)	1990-2015	10 countries, LatAm	Cointegration Test	CO_2 Emissions	GDP (logarithmic equation)	Not confirmed
Bulut (2019)	2000-2018	USA	Cointegration Test	CO_2 Emissions	Renewable energy consumption	Confirmation
Arango-Miranda et al. (2020)	1994-2020	USA, Canada, and Mexico	OLS, VAR	Environmental Degradation	CO_2 emissions, energy consumption, GDPpc & Trade Openness	Confirmated (USA & Mexico) Not Confirmated (Canada)
Ortiz-Paniagua y Gómez (2021)	1970-2016	19 countries, LatAm	Cointegration Test	CO_2 Emissions	GDPpc, GDPpc²	Confirmated
Bekun et al. (2021)	1995-2016	E7 economies (2 from LatAm)	OLS	CO_2 Emissions	GDPpc	Confirmated
Haider et al. (2022)	1970-2020	Canada	ARDL	N2O Emissions	GDPpc, GDPpc², ALU, exports	Confirmated
Taghvaee et al. (2022)	1971-2016	OCDE countries	GMM	CO_2 Emissions	GDP	Confirmated
Zeraibi et al. (2023)	1990-2019	22 countries (6 from LatAm)	OLS	CO_2 Emissions	GDPpc, Public Debt, Renewables Electricity Production	Confirmated
Magazzino et al. (2023)	1870-2008	9 countries (Canada)	OLS, FE	CO_2 Emissions	GDPpc, GDPpc², Energy Consumption, Openness	Confirmated
Wang, Zhang & Li (2023)	1990-2018	208 countries (31 from America)	GMM	CO_2 Emissions	GDPpc, Human capital index, Renewable energy consumption, Total resources rents, and Trade	Confirmated
Acevedo-Ramos et al. (2023)	1970-2018	Colombia	ARDL	CO_2 Emissions Ecological Footprint CH_4 Emissions	GDPpc, FDI, Non-REU, REU, Urban Population, Industry, Agriculture, Forestry and Fishing	Confirmated

Note: LatAm: Latin America; OLS: Odinary Least Squares; VAR: Vector Analytic Regression; FE: Fixed Effect; ARDL: Autoregressive Distributed Lag; GMM: Generalized Method of Moments; N2O: Nitrous Oxide; CH4: Methane; GDP: Gross Domestic Product; GDPpc: Gross Domestic Product per capita; ALU: Agriculture Land Use; FDI: Foreign Direct Investment; REU: Renewable Energy Use

Table 2. Variables and expected signs of the coefficients.

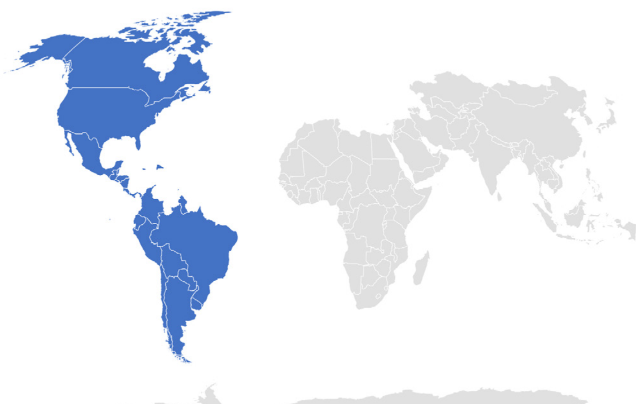
Nomenclature	Name/unit	Definition	Sign
PC emissions	CO2 emissions per capita (tonnes)	Human activities, especially in the transport, industry, and electricity generation sectors, are the primary sources of carbon dioxide (CO2), although there is also a natural contribution through the terrestrial carbon cycle. Per capita CO2 emissions reflect the amount of this greenhouse gas emitted by each individual and constitute a key indicator. (EPA, 2023).	
GDPPC	Gross Domestic Product per capita (US$ at current prices)	It is an indicator that illustrates the sum of money each country's citizen would receive in the event of an equal distribution of the Gross Domestic Product generated by that nation in a given year. (INEGI, 2023).	Positive
GWh	Electrical energy consumption (GWh)	It refers to the energy available in the country and used for different purposes. (SEMARNAT, 2023).	Positive
IPI	Total tax revenue (millions of dollars)	They are the revenue collected by the government expressed as a percentage of the Gross Domestic Product (GDP), which shows how much economic production a country collects through taxes (OECD, 2020).	Negative
I/E GDP	Imports/Exports as a percentage of GDP (% of GDP)	It refers to the calculation in money terms of all transactions of goods bought and sold by a country with other countries during a specific period of GDP (SEMARNAT, 2016).	Positive

Source: Elaboration own, 2024.

structural elements, specifically the years and nations involved in this case. This data type provides certain advantages since it considers individual differences and how they change over time. Additionally, it enables the analysis of more complex models (Gujarati & Porter, 2010).

The period analyzed was from 2010 to 2020, and the selected countries were chosen based on their importance in America (Figure 1), their size and their available information; these are Canada, the United States, Mexico, Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama, Bahamas, Barbados, Jamaica, the Dominican Republic, Trinidad and Tobago, Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru and Uruguay. Likewise, these data were obtained from official sources such as the Organization for Economic Cooperation and Development (OECD), the World Bank, and other statistical sources.

Figure 1. Countries of America analyzed.



Source: Own elaboration with Bing Technology 2024

4. Results

4.1. Mathematical form of the model

$$PC\ Emissions = 0.0003\ GDP\ PC_{[it]} + 2.521e\text{-}06\ GWh_{[it]} - 3.739e\text{-}06\ IPI_{[it]} + 2.9035\ I/E\ GDP_{[it]} + \alpha_i + \varepsilon_i \quad \text{[Ec. 2]}$$

The equation was obtained by running the final model in Python programming language Jupyter Notebook with the linear model library using a PanelOLS with Numpy. First, a traditional fixed-effects model was run. However, a static panel regression model was run without fixed effects or time effects with clustering in the residuals to correct the standardized error variance for autocorrelated errors. This allowed correcting the standardized error variance for autocorrelated errors within each entity and the standardized error variance for the time series, obtaining the results shown in Table 3.

Table 3. Results general model

PanelOLS Estimation Summary

Dep. Variable:	Emissions pc	R-squared:	0.7420
Estimator:	PanelOLS	R-squared (Between):	0.7478
No. Observations:	275	R-squared (Within):	0.0236
Date:	Fri, Aug 25 2023	R-squared (Overall):	0.7420
Time:	11:19:08	Log-likelihood	-764.82
Cov. Estimator:	Clustered		
		F-statistic:	194.82
Entities:	25	P-value	0.0000
Avg Obs:	11.000	Distribution:	F(4,271)
Min Obs:	11.000		
Max Obs:	11.000	F-statistic (robust):	3909.9
		P-value	0.0000
Time periods:	11	Distribution:	F(4,271)
Avg Obs:	25.000		
Min Obs:	25.000		
Max Obs:	25.000		

Parameter Estimates

	Parameter	Std. Err.	T-stat	P-value	Lower CI	Upper CI
GDP PC	0.0003	3.706e-05	8.0875	0.0000	0.0002	0.0004
GWh	2.521e-06	5.812e-07	4.3373	0.0000	1.377e-06	3.665e-06
Tax	-3.739e-06	1.321e-06	-2.8303	0.0050	-6.341e-06	-1.138e-06
I/E GDP	2.9035	1.6719	1.7367	0.0836	-0.3880	6.1950

Source: Elaboration own, 2024.

It was decided to include the variable Imports/Exports as a percentage of GDP (I/E GDP) although it is acceptable only at a level of 90% because its parameter turned out to be considerable and gives us a good contribution to the prediction of the model, fortunately this through the increase of the R square.

4.2. Choosing the appropriate econometric technique

The compare function was used to compare the optimal model between the static panel regression model without fixed or time effects and one with random effects. The results obtained from this test showed that the static model is superior, as shown in Table 4.

Since the highest T-stats values are found in the static model, with a better R square and a P-value of 0.0000, it was decided to stick with the static panel regression model. The P-value allows to compare the variables Gross Domestic Product per capita (GDP PC), Electrical energy consumption (GWH), Tax revenue (TAX), and Imports/Exports as a percentage of GDP (I/E GDP) in the Static panel with the Random effects.

4.3. Evaluation of the estimates

Based on the model's results, it was concluded that the parameters are statistically satisfactory because the coefficient of determination (R2) was high, and all the P-values were below 0.10.

Also, in creating the model, the square of the coefficient of determination was used as a tool to

Table 4. Comparison of Static Panel Model and Random Effects

Model Comparison

	Static panel:	RANDOM effects:
Dep. Variable	Emissions pc	Emissions pc
Estimator	PanelOLS	RandomEffects
No. Observations	275	275
Cov. Est.	Clustered	Unadjusted
R-squared	0.7420	0.3332
R-Squared (Within)	0.0236	0.2513
R-Squared (Between)	0.7478	0.6618
R-Squared (Overall)	0.7420	0.6585
F-statistic	194.82	33.860
P-value (F-stat)	0.0000	0.0000
GDP PC	0.0003	0.0001
	(8.0875)	(5.7680)
GWh	2.521e-06	3.458e-06
	(4.3373)	(3.7127)
Tax	-3.739e-06	-2.46e-06
	(-2.8303)	(-6.5124)
I/E GDP	2.9035	3.4241
	(1.7367)	(7.7896)

T-stats reported in parentheses

Source: Elaboration own, 2024.

observe the statistical reliability of the estimates of the model parameters, which was 0.7420. This resulted in an acceptable parameter within the study of social sciences.

4.4. Evaluation of the predictive power of the estimated model

Below, the model's function is evaluated, taking the mean of the data as values for the variables and Eq. 2 as a basis.

$$PC\ Emissions = 0.0003(13004) + 2.521e\text{-}06\ (2.3e+05) - 3.739e\text{-}06\ (2.054582e+05) + 2.9035\ (0.576220) + \alpha_i + \varepsilon_i \quad [Ec.\ 3]$$

PC Emissions = 5.38tCO_2

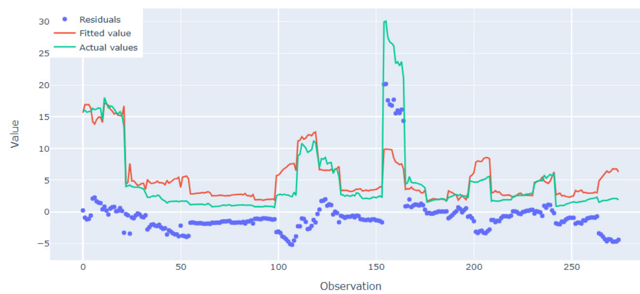
According to the model, if we consider a GDP per capita of 13,004 dollars, energy consumption of 230,000 Gwh, tax revenues of 205,458 million dollars, and 57.6% of imports/exports as a percentage of GDP, the result is an average of 5.38 tons of carbon dioxide per year per country.

4.5. Analysis of model results

We conducted a graphic analysis to evaluate the final model's results. This analysis contrasts the estimated results with the real values and their residuals, providing a comprehensive evaluation of the model's performance.

Figure 2 shows the results of the static panel regression without fixed effects or time effects for the 25 American countries, which were the object of study in this research, from 2010 to 2020. First, the results are shown. Residuals capture their random distribution and constant variance without an identifiable pattern, which indicates the correct fit of the data. In addition, it provides a graphical representation that allows the observed data to be contrasted with the model estimates, which is essential to evaluate the forecasting capacity of the model. As evident, there is a notable agreement between the real data and those fitted by the model, which indicates an adequate calibration of the model.

Figure 2. Static panel model with current, adjusted, and residual values



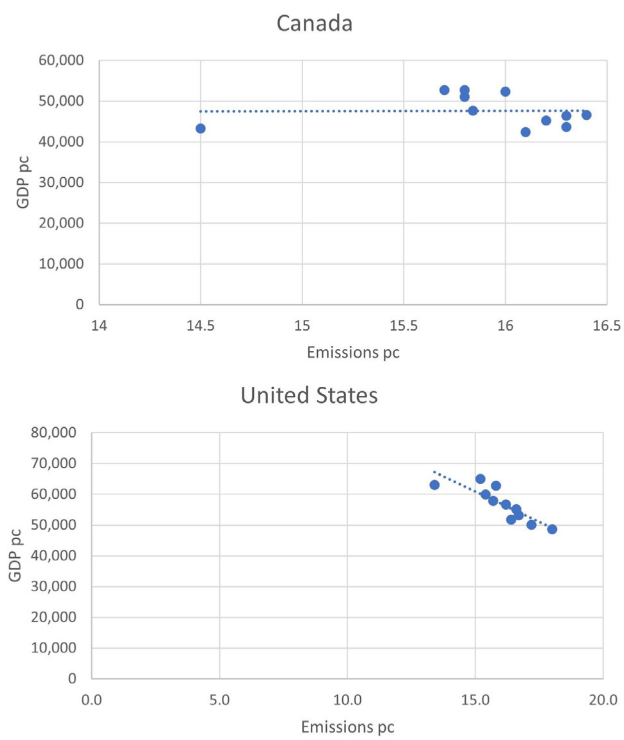
Source: Elaboration own, 2024.

4.6. Analysis of the Kuznets curve in some countries

A graphical analysis of some countries was conducted to determine whether the Kuznets curve is fulfilled in the countries analyzed. In the case of developed countries, Canada and the United States were analyzed, finding that in the case of the United States, the hypothesis that as the economy progresses, there is a decrease in its emissions is fulfilled, as shown in Figure 3, however, in Canada no clear trend was found for the period analyzed (2010-2020).

On the contrary, in emerging countries, taking Mexico and Brazil as a reference (Figure 4), it was found that both have a positive slope, fulfilling the hypothesis of the Kuznets Curve, which tells us that in the initial stages of economic development, a country tends to increase its environmental degradation because it is in a stage of increasing urbanization and increasing its industrial production. Although the empirical evidence found confirms the ECK hypothesis, there could be other exogenous variables related to such behavior,

Figure 3. Kuznets curve in developed countries of America**.**



Elaboration own, 2024.

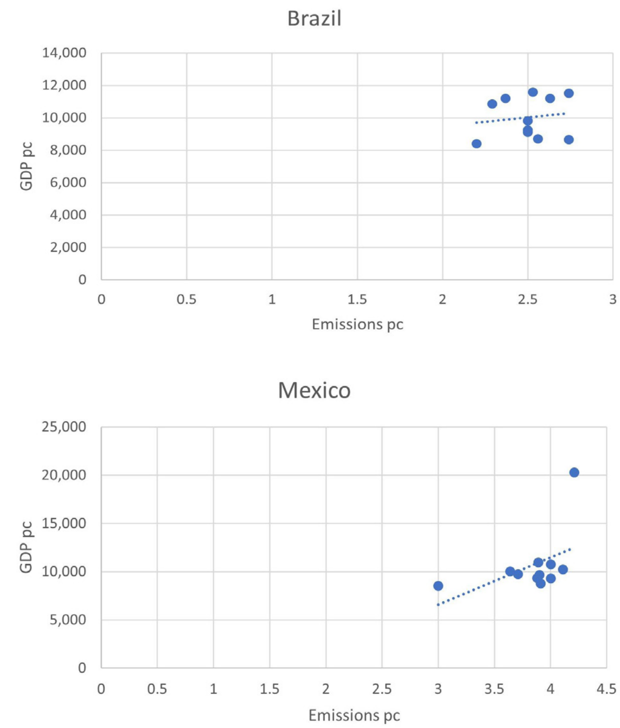
including stricter environmental regulations in developed countries and specific taxes on CO2 emissions. It is important to note that international pressure within the framework of the Sustainable Development Goals (SDG) could also define the recent behavior of the ECK.

In the period analyzed, the Kuznets curve is generally fulfilled as, in most cases, reaching their inflection peak is necessary for countries to reduce emissions or for the government to implement more rigorous environmental policies.

5. Discussion

Various studies explain the relationship between environmental degradation and other variables, known as the expanded EKC; other explanatory variables are added to the original proposal. Thus, the results obtained in the present research work confirm the existence of an EKC for the countries of America in the period 2010-2020 through a panel data model, where CO_2 emissions are measured and their relationship with the variables GDP per capita, electricity consumption, income from environmental taxes, exports, and imports in America.

Figure 4. Kuznets Curve in some emerging countries in America.



Source: Elaboration own, 2024.

Previous studies used panel data models to test the EKC hypothesis and have obtained results similar to and different from this research. Among them, Zeraibi et al. (2023) argue that for emerging economies from 1990 to 2020, through an ordinary least squares model, there is a relationship between CO2 emissions and GDP per capita in the form of N; that is, the EKC hypothesis is confirmed. However, in the form of an N, not an inverted U for the region's countries, this form is sensitive if the sample of countries is modified.

In addition, the results of Pradhan et al. (2024) argue that, among developing countries in the South Asian region, with data spanning from 1996 to 2021, there is an inverted U-shaped relationship between CO_2 emissions, energy consumption, and economic growth; the authors show that higher per capita income encourages higher energy consumption. In addition to emissions, financial development, and population growth positively affect energy consumption in the countries considered to be in Asia.

Regarding environmental taxes, Vallés-Gimenez and Zarate-Marco (2021) analyze, in the context of the EKC, the determinants of the export intensity of hazardous industrial waste among Spanish regions, with particular attention to the influence of waste taxes and environmental policies in their findings, they suggest that there is a dynamic spatial component in export intensity and that both regional taxes on waste disposal and the stringency of environmental policies seem to incentivize, albeit modestly, the rate of waste exported to other regions.

The variable imports and exports of GDP, like the findings of Boamah et al. (2017) that when investigating the role of international trade in China (considering total exports and imports) in mitigating CO_2 emissions as the nation advances economically, there is a long-term N-shaped relationship between economic growth and emissions, within the framework of the estimated EKC. Therefore, the recommendation is that China, as a leading exporter, should transform its trade growth mode by reducing CO_2 emissions and strengthening its international cooperation while adopting more environmental protections.

As a political implication, some measures must be taken to reduce environmental pollution without sacrificing countries' economic growth. Some of these measures involve reducing greenhouse gases from industry, transport, and heat, increasing the use of biodiesel, and applying environmental technologies. It is not expected that the policies will be applied homogeneously in the countries since they would have different impacts depending on each country's stage of development and even the estimation of its position in the EKC.

A higher per capita income represents a technological evolution that implies the reduction of environmental pressures. In turn, technological progress, which can be reflected in the production of goods and services under stricter environmental protection standards, encourages producers to innovate and, therefore, reduces CO_2 emissions and, in general, various pollutants that degrade environmental quality at a local and global level, in the short and long term. This impact can be seen in the coefficient of exports for the model, as it turns out to be significant because these exports made by countries in the American continent are generally under more lax environmental protection standards.

6. Conclusions

The hypothesis for the EKC was tested for 25 countries on the American continent between 2010 and 2020 through an econometric approach that involved the analysis of a model with panel data. The empirical evidence presented in this paper allows us to visualize an inverted U-shaped association between environmental degradation and the variables considered to test the EKC. The estimates have the expected signs and are statistically significant, resulting in empirical support for the acceptance of the EKC hypothesis in America.

Thus, there is a significant effect of GDP per capita, electricity consumption, GDP imports and exports, and taxes related to the environment on CO_2 emissions. Although it is recognized that the relationship may differ between countries (OECD, 2013), those that make up the American continent are responsible for more than 20% of global CO_2 emissions. The estimates of the EKC hypothesis in different countries should be considered an essential tool for effectively constructing environmental policies since environmental regulation has a moderating effect on CO2 emissions.

One of the limitations of this research is that, as with most econometric models, they can not explain the entire relationship between the dependent variable and the independent variables, as they can often be complex and multidimensional, making it difficult to fully represent them. For example, this article did not consider CO2 emissions from natural sources (volcanoes, swamps, natural forest fires, among others), which can generate biases in the results.

Therefore, as future lines of research, considering the ECK hypothesis, it would be pertinent to explore the inclusion of additional factors that may influence the relationship between GDP and CO2 emissions, such as emissions of natural origin, which were not considered in this study. In addition, more complex econometric models could be incorporated to better capture the interaction of variables that are not directly observable; addressing the influence of climatic and geological phenomena on emissions and developing a more holistic approach that considers these external elements.

The findings of this study strongly recommend that policymakers propose comprehensive energy and economic policies aimed at encouraging balanced growth in the countries' regions, considering in their agendas actions that involve the different sectors in incorporating renewable energies that allow improving environmental quality and reducing the ecological footprint.

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