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On the Nexus between Economic growth and Environmental Degradation in 28 Countries Classified by Income Level: A Panel Data with an Error-components Model

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ABSTRACT

This paper aims to examine the relationship between economic growth and environmental degradation in a sample of 28 countries. A panel data model is used dividing the sample into four groups classified by income level where fixed and random individual effects are estimated without the time component using an error-components model (ECM). Annual data from the World Bank for carbon dioxide emissions per capita and gross domestic product per capita are used for the period 1970-2016. The empirical results and their graphical analysis, using a panel data approach with an ECM, suggest an absence of an Environmental Kuznets Curve (EKC) in the whole sample. These results considering panel data with an ECM, 28 countries and 46 years differ from many of the studies that support the existence of an EKC in similar samples.

Keywords: CO_2 Emissions, Economic Growth, Panel Data Model, Error-components Model, Environmental Kuznets Curve
JEL Classifications: Q53, F43, F46, C50

1. INTRODUCTION

Throughout the world, the last few decades have seen an increase in industrial production and its effect on economic growth. However, industrial production generates various pollutants, including carbon dioxide (CO_2) gas. This CO_2 is produced and released into the atmosphere mainly when fossil fuels are burned. Since the industrial revolution, it appears that the burning of fossil fuels has caused an increase in CO_2 concentrations in the atmosphere. In addition, this combustion rate has increased during the last decades. At the same time, the economic growth of many countries sustained by the burning of fossil fuels seems to increase environmental degradation without distinguishing between developed and underdeveloped economies.

At present, there are many environmental problems like loss of biodiversity, ocean acidification, rivers and sea pollution, desertification, CO_2 emissions, etc. Together all these problems are regarded as climate change. Climate change is a worry for the future of human development if it reaches a non-sustainable point, which has been the focus of several climate summits. It has been claimed in these summits that environment deterioration may hinder Gross Domestic Product (GDP) growth and, particularly, it can superimpose a problem for the species survival. The climate change problem is even so imperative that the United Nations Organization (UNO, 2015) created the Sustainable Development Goals (SDG). These goals aim to address current and future environmental problems as CO_2 emissions. From the 17 objectives of the SDG, five of them are directly related with favoring life on the planet.

This investigation examines the relationship between economic growth and environmental degradation through the possible existence of an Environmental Kuznets Curve (EKC) in a sample of countries (Kuznets, 1955). It is assumed that an EKC could technically reveal how a measure of environmental quality, such as

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the CO_2 per capita emitted by a country, can change as economic growth increase. To study this link between economic growth and CO_2 emissions, an assessment of this nexus is carried out for 28 countries, classified into four groups by income level, using panel data in conjunction with an error-components model (ECM) during the period 1970-2016 on an annual basis. The sample of 28 countries is divided as follows: low income countries (Congo Democratic Republic, Niger, Rwanda, Sudan, Sierra Leone, Togo, Uganda), lower middle income countries (Bangladeshi, Belize, Honduras, Kiribati, Nigeria, Nicaragua, Salvador), upper middle income (Argentina, Brazil, China, Guatemala, Mexico, Peru, Thailand), and high income (Canada, France, Japan, Qatar, Norway, United Kingdom, United States).

It is worth mentioning that this paper fills a gap in the EKC-related literature by presenting new insights as follows: (a) includes an ECM that separates the time component of individual random and fixed effects by providing uncorrelated estimates over time, (b) implements the Hausman test to determine which ECM specification offers a better statistical fit, (c) provides a graphical analysis of the estimates obtained, and d) ranks the world's richest countries in the high income group.

This document is organized as follows: Section 2 provides a brief literature review; section 3 examines the descriptive statistics and the dynamics of the variables considered for this study, GDP and CO_2 emissions both in per capita terms; section 4 specifies the econometric panel data with an ECM; section 5 reports and discusses the empirical results, as well as examines whether an EKC is observable in this panel study; finally, section 6 gives the conclusions.

2. LITERATURE REVIEW

The literature concerning the EKC has two principal venues. In the first one, theoretical models postulate that after certain conditions are met, the EKC can be achieved in the real world. The EKC might explain the relationship between economic growth and environmental quality. This curve has an inverted "U" shape. If the income is plotted in the abscissa axis versus the emissions in the ordinate axis, it is expected an inverted "U" shape. In the ascending part of this curve countries use a technology based on burning fossil fuels. At the turning point of this curve there is an optimal level of income and wealth accumulation after which environmental degradation is reversed. Then, the technology shifts from burning fossil fuels to clean and renewable energies (electric, solar, eolic, etc.). This shift could cause lower levels of pollution, since clean technologies are expected to have less CO_2 emissions and, therefore, hurt less the environment. In this sense, Grossman and Krueger (1991) suggest the existence of an EKC for Mexican air pollutants (suspended particulates). Likewise, Beyene and Kotosz (2020) find the existence of an EKC for several East African countries. Moreover, Apergis and Ozturk (2015) apply a Generalized Method of Moments (GMM) methodology using panel data to test the EKC hypothesis finding empirical support for it. Moreover, Jebli et al. (2016) verify the existence of the EKC for 25 Organization for Economic Cooperation and Development (OECD) countries spanning the period 1980-2010. Other more recent papers related to the confirmation of an EKC can be found in: Valencia-Herrera et al. (2020) that analyze the relations among economic growth, energy-electricity consumption, CO_2 emissions, and urbanization in Latin America; Santillán-Salgado et al. (2020) that study the interactions among CO_2 emissions, GDP, energy consumption, electricity use, urbanization, and income inequality for a sample of 134 countries; Salazar-Núñez et al. (2020) that assess the impact of energy consumption and CO_2 emissions on economic growth in 79 countries grouped by income level; Salazar-Núñez et al. (2022) that revise the interdependence among renewable and non-renewable energies, economic growth, and CO_2 emissions in Mexico; Mendoza-Rivera et al. (2023) that examine the relations among renewable and non-renewable energy consumption, and CO2 in North America; Konya (2022) and Suki et al. (2020) that find evidence of an EKC in several developing countries; Maneejuk et al. (2020) that verify the existence on an EKC in a small subset of countries; and Freire et al. (2023) that show a corroboration of the EKC hypothesis in Brazilian states for carbon dioxide and nitrous oxide.

In the second venue, empirical models demonstrate that the theoretical EKC does not exist and fail to explain the relationship between income and environmental degradation. The EKC is sometimes related to the rate of investment in research and development, pollution consequences, lack of pro-environment policies, or a lower technological progress that does not allow a technology transition from burning fossil fuels to clean energies. If some of these factors are not present, then the inverted "U" shaped behavior may not be observable in the real world. In this sense, Bhattacharyya and Ghoshal (2010) show empirically that the expected inverted "U" curve relationship between economic growth and environmental degradation is not achieved in countries with high rates of economic growth and larger populations. Likewise, Dasgupta et al. (2002) show that the expected inverted "U" is not observable due to institutional failures. Some other authors that have found similar results are: Ansari et al. (2020), Soytas et al. (2007), Roca and Padilla (2003), and Seppälä et al. (2001). On the other hand, He and Richard (2010) find little evidence in favor of the EKC hypothesis. Kumar-Kar (2022) finds that the inverted U-shaped EKC hypothesis does not hold in Baltic countries (Estonia, Latvia and Lithuania). Destek and Sinha (2020) found after using second generation panel data methodologies which allow to cross-sectional dependence among countries that the inverted U-Shaped EKC hypothesis is not fulfilled in the OECD member countries for the period from 1980 to 2014. Moreover, Baek (2015) finds that in 12 countries, CO_2 emissions tend to decrease monotonically with income growth, providing no evidence in support of the EKC. Also, Saidi and Mbarek (2017) results show a positive monotonic relationship between income and CO_2 emissions which do not support the EKC hypothesis. Frodyma et al. (2022) study the European Union (EU) countries in the period between 1970 and 2017 by testing three EKC specifications, their results reveal that the EKC models fail to explain the relationship between income and emissions and no long-term relationships were detected. Grossman and Krueger (1996) and Stern et al. (1996) critic the EKC concept of an inverted-U relationship between economic growth and environmental damage because they considered it is a reduced-form relationship that demonstrates correlation rather than a causal mechanism of growth affecting environment. Arrow et al. (1996) also critics the U shaped of the EKC, because they explain that it depends on the assumption that world per capita income is normally distributed when in fact median income is far below mean income, and that there is no feedback from the quality of the environment to production possibilities, and in which trade has a neutral effect on environmental degradation. Stern (2018) mentions that EKC estimated models are not statistically robust since studies of the relationship between per capita emissions and income that attempt to avoid various statistical pitfalls find that per capita emissions of pollutants rise when increasing per capita income and the other factors remain constant, and concludes that there is still no consensus on the drivers of changes in pollution since the mechanisms that might drive such patterns are not still contested. Stern (2001) mentions that no progress has been made on both understanding the EKC phenomenon and on addressing the various criticism raised against some of the empirical studies and their interpretation in the policy literature, since empirical decompositions of the EKC into proximate or underlying causes are either limited in scope or non-systematic, and explicit testing of the various theoretical models has not yet been attempted. Stern and Common (2001) suggest that the EKC is an essentially empirical phenomenon, but most of the EKC literature is statistically weak, because it is very easy to do bad econometric specifications, and the history of the EKC exemplifies what can go wrong. Finally, Perman and Stern (2003) use newly developed panel unit root and cointegration tests to consider serial dependence and random walk trends in time series, the authors find that the EKC does not exist in 74 countries over a span of 31 years, since it seems that most indicators of environmental degradation are monotonically rising in income.

After the brief review of the literature above, we agree with Dinda (2004) that carries out a comprehensive review of the EKC literature in that the evidence for the existence of the EKC has been challenged from various points of view. There is no agreement in the literature on the income level (turning point) at which environmental degradation is reversed (when possible). In a similar study carried out by Dasgupta et al. (2002) it is mentioned that empirical researchers are far from agreeing that the EKC always provides a good fit, even for conventional or local contaminants. In one of the most comprehensive reviews of the empirical literature, Stern (1998) argues that the evidence for the inverted-U relationship applies only to a subset of environmental measures; for example, air pollutants such as suspended particles and sulfur dioxide. Similarly, Grossman and Krueger (1993) find that suspended particles monotonically decrease with income. Finally, Stern et al. (1998) find that sulfur emissions increase over the existing income range and that the results for water pollution are similar.

3. DATA NATURE

3.1. Descriptive Statistics

The descriptive statistics reported below, in Table 1, are mean, standard deviation, coefficient of variation and kurtosis for the series GDP per capita (*GDPpc*) and CO_2 emissions per capita (*CO_2pc*). Appendix 1 shows the data sources and the units in Table A1.

Table 1 shows that *GDPpc* has an average of 27,797 for the group of high income countries, for upper middle income countries the average *GDPpc* obtained is 3,266, for low middle income countries the value is 1,235, and for the low-income group is only 371. Regarding the coefficient of variation, according to Table 1, for the group of high income countries its value is 0.64, for the group of upper middle income is 0.74, for the group of middle income is 0.55, and for the low income countries is 0.48. The highest value for the coefficient of variation corresponds to the upper middle income group, indicating that this group is the most dynamic in *GDPpc*. The lowest coefficient of variation corresponds to the group of low-income countries, which makes this group the least active in *GDPpc*.

With respect to Table 1, the standard deviation for high income countries is 17,871, for the upper middle income countries is 2,421, for low middle income countries is 684, and for the low income countries is 176. This last value is approximately 3.8 times smaller than that for the group of lower middle income countries, 13.7 times smaller than that for upper middle income countries, and 101 times smaller than that for high-income countries. Perhaps, this low income values denotes a small variation in *GDPpc*, and thus a relative low capacity to growth.

The last statistic to be analyzed for the *GDPpc*, in Table 1, is the kurtosis. The corresponding value for the high income group is 2.01, for the group of upper middle income countries is 2.80, for low middle income countries is 2.42, and for the group of low income countries is 3.30. Notice that in all groups the kurtosis is positive. This statistic indicates data outliers; the higher the kurtosis value, the flatter the distribution curve of data. Table 1 indicates that the *GDPpc* presents a type of platykurtic kurtosis, for which it is concluded that its distribution, for all groups, contains many outliers and a flattened shape.

Next, the descriptive statistics for the variable *CO2pc* are presented below. Table 1 shows that this variable has a mean for high income countries of 16.01, for upper middle income countries of 2.28, for lower middle income countries of 0.74, and for low income countries is only of 0.14. The latter is about 100 times smaller than the mean for high income countries. This data indicates that poor countries pollute the less. The coefficient of variation for the group of high income countries is 0.17, for the group of upper middle income is 0.27, for the group of lower middle income countries is 0.21, and for the group of low income is 0.20. The last two values are very similar indicating perhaps that pollution behavior in the two poorest groups of countries is somehow related.

According to Table 1, the standard deviation of *CO2pc* shows a value of 2.74 for high income countries, for the upper middle income group is 0.62, for the lower middle income countries is 0.15, and for the group of countries with low income is 0.03. As it can be seen, the difference between the low income countries compared with high income countries is 91 times lower. Therefore,

Table 1: Summary statistics

Variables	Variable mean (SD)	Coefficient of variation (kurtosis)
GDPpc		
High income	27,797 (17,871)	0.64 (2.01)
Upper middle income	3266 (2421)	0.74 (2.80)
Lower middle income	1235 (684)	0.55 (2.42)
Low income	371.13 (176)	0.48 (3.30)
CO2pc		
High income	16.01 (2.74)	0.17 (3.22)
Upper middle income	2.28 (0.62)	0.27 (2.29)
Lower middle income	0.74 (0.15)	0.21 (3.95)
Low income	0.14 (0.03)	0.20 (2.03)

Groups of countries by income level, 1970–2016, annual observations. Countries classified by income level group are reported in Appendix 2 in (Tables A2 and A3). *GDPpc* units are in USD at current prices, *CO2pc* units are in metric tons. Source: Own elaboration based on data from the World Bank and using Stata 17 MP. SD: Standard deviation

the group of countries that pollutes the most is, as expected, the high income group.

Regarding the *CO2pc* coefficient of variation, in Table 1, the low income countries group has a value of 0.20. This value is close to the other three income groups, *i.e*., 0.21 for lower middle income, 0.27 for upper middle income, and 0.17 for high income. Perhaps these values exhibit similar technologies (based on burning fossil fuels), as the rate of variation of these emissions are quite similar. The countries with a similar coefficient of variation are the medium low and low income groups, since *CO2pc* emissions have values of 0.21 and 0.20, respectively.

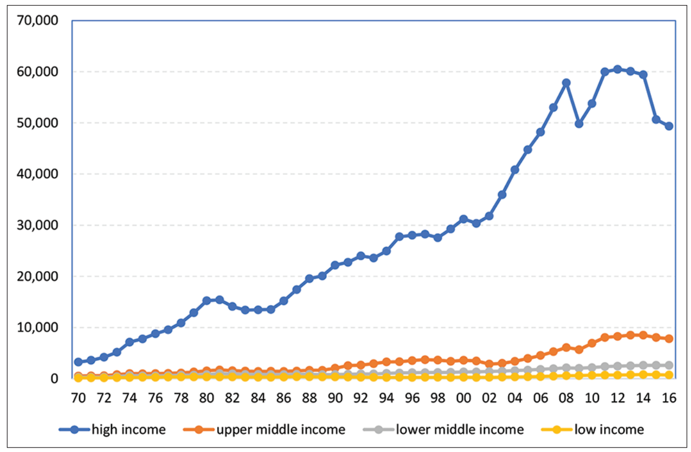
Finally, from Table 1, the last statistic to report on *CO2pc* emissions is the kurtosis. For the high income group is 3.22, for the upper middle income countries is 2.29, for the group of countries with lower middle income is 3.95, and for the low income group is 2.03. As it can be seen, the countries belonging to the lower middle income group present the highest kurtosis from the four country groups. Given this last value, it is suggested that *CO2pc* in this group have the greatest outliers among the groups of countries under study.

3.2. Graphical Analysis

Figures 1 and 2 are shown below, which are generated with annual data for *GDPpc* and *CO2pc* for the period of 1970 to 2016. Here, countries are classified by income group in the same way as in Table 1. These figures help visualize the performance of these variables over time.

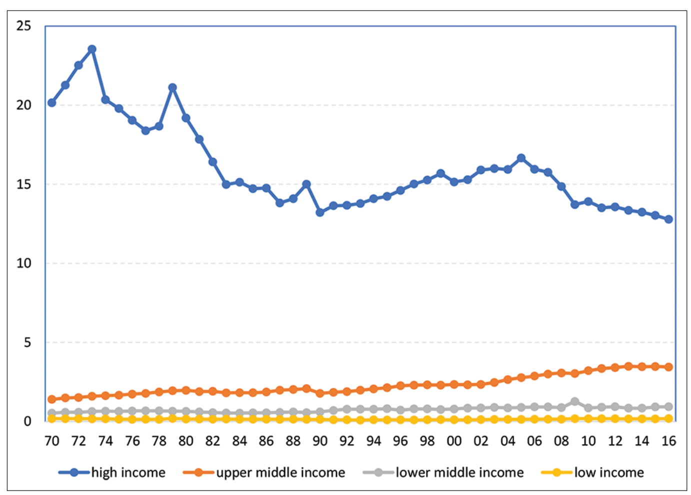
Figure 1 illustrates the dynamics of *GDPpc* for all groups throughout the period 1970-2016. This Figure shows that the group of countries that belong to the high income group (indicated in blue) had a *GDPpc* of approximately 3,200 USD in 1970, later in 2008 it reached a level of 57,821 USD, and in 2009 it had a decrease of 8,000 USD when compared to the previous year. Its maximum level was in 2012 with a value of 60,500 USD. From 2013 to 2016, this income decreased reaching 49,349 USD in 2016. The upper middle income group (shown in orange) shows a *GDPpc* of 523 USD in 1970, which compared to the *GDPpc* of high income countries is about 6 times smaller. It presents a steeper slope in 2013 with a value of 8,514 USD. For a better visualization of the series without the effect that high income countries have on the *GDPpc* scale in Figure 1, Figure AG1 located in Appendix 3.

Figure 1: *GDPpc* in USD. Groups of countries classified by income level: low, lower middle, upper middle and high, 1970-2016 annual



Source: Own elaboration based on data from the World Bank

Figure 2: CO_2 emissions per capita in metric tons. Groups of countries classified by income level: low, lower middle, upper-middle and high, 1970-2016 annual



Source: Own elaboration based on data from the World Bank

The group of lower middle income countries (shown in gray) had an average *GDPpc* in 1970 of 282 USD. At the end of 2016 this indicator reached the level of 2,610 USD. For a better visualization of this group evolution Figure AG2 located in Appendix 3. As for the low income group (in yellow), the *GDPpc* in 1970 was 147 USD, for the year 2016 the level of this

GDPpc is barely 725 USD. The group of low income countries has a poor evolution when compared with the other groups. For a better visualization of the scale of this income group Figure AG2 located in Appendix 3.

Figure 2 shows the *CO2pc* with annual observations from 1970 to 2016 for all the groups. In the group of high income countries (in blue) despite of being the income group with the greatest amount of *CO2pc*. This indicator has a downward trend, starting in 1970 with 20.15 metric tons per capita. The downward trend reaches the year 2016 with a value of 12.78 metric tons per capita. The group of upper middle income countries (orange color) shows an upward trend in this indicator during the period analyzed. For the year 1970, this income group presents a minimum value of 1.40 metric tons of *CO2pc*, but with constant increases until 2016 when there is a value of 3.44 metric tons per capita. Its highest value is 3.49 metric tons per capita in 2013. For a closer view, Figure AG3 in Appendix 3. The group of countries with lower middle income (gray color) shows, in the same way as in the previous group, an upward trend. In 1970, this group has emissions of 0.59 metric tons of *CO2pc*, this being its lowest level. The highest level for this group of countries was positioned in 2009 with 1.27 metric tons. To visualize these income groups with a greater detail refer to Figure AG4 located in Appendix 3. Finally, the low income group (yellow color) has the smallest value of *CO2pc*. For this income group the period from 1980 to 1993 has witness a significant decrease in *CO2pc*, but as from 1994 its emissions have increased, in order to better appreciate this Figure AG5 in Appendix 3.

4. PANEL DATA WITH AN ERROR-COMPONENTS MODEL

The econometric analysis proposed in this paper is a panel data in conjunction with an ECM. The ECM is estimated to distinguish error components such as those introduced by time and individual panel dimensions. This analysis will help us investigate whether an EKC exist for the 28 countries grouped by income level over the period of 1970-2016.

The panel data model is presented below, which is composed by two equations. The first equation includes a quadratic term to account for the expected curvature of the EKC. The second equation will be stated in subsection 4.2, which is an Error-Components Model (ECM) that separates from the first equation error term, time and individual components. The panel data model is given by:

$$CO2\,pc_{it} = \beta_{0it} + \beta_{1it} GDPpc_{it} + \beta_{2it} GDPpc_{it}^2 + u_{it} \qquad (1)$$

Where $CO2pc_{it}$ represents carbon dioxide emissions per capita in metric tons, $GDPpc_{it}$ stands for the gross domestic product per capita in USD, where represents four income country groups ($i = 1$ for high income, $i = 2$ for upper middle income, $i = 3$ for lower middle income, $i = 4$ for low income), at time t (t = 1970,…, 2016), $GDPpc_{it}^2$ represents the gross domestic product per capita squared for each individual i at time t, β_{0it} is the intercept estimator for individual i and time t, β_{1it} is the slope estimator for individual i and time t, β_{2it} is the estimator of the quadratic term for individual i and time t, u_{it} is the error term for individual i and time t. The quadratic term is intended to measure the EKC curvature.

4.1. Quadratic Specification

The quadratic specification in equation (1) is, first, estimated without effects. Also, equation (1) is estimated for fixed and random effects for individuals. The estimation method is Ordinary Least Squares (OLS). The hypotheses about the signs of the estimators on equation (1) are presented below. In the following hypotheses the estimator sub-indices for the panel dimensions i and t are written if their effects are under analysis. If they are not written, then it is assumed that they do not change.

4.1.1. Quadratic specification: Hypothesis 1, no effects $\beta_0 = 0$, $\beta_1 = 0$, and $\beta_2 = 0$

If the null hypothesis is $\beta_1 > 0$ and $\beta_2 = 0$, it would express an increasing relationship between *CO2pc* and *GDPpc*, in which high levels of income would be associated with high levels of carbon dioxide emissions. The alternative hypothesis is $\beta_1 \ngtr 0$ and $\beta_2 \neq 0$. If the null hypothesis is $\beta_1 < 0$ and $\beta_2 = 0$, it would express a decreasing relationship between *CO2pc* and *GDPpc*, in which low income levels are associated with low carbon dioxide emission levels. The alternative hypothesis is given by $\beta_1 \nless 0$ and $\beta_2 \neq 0$. Finally, if the null hypothesis is $\beta_1 > 0$ and $\beta_2 < 0$, it would express a slope shift on the EKC. This case would represent high income levels associated with decreasing levels of pollution. The alternative hypothesis is $\beta_1 \ngtr 0$ and $\beta_2 \nless 0$, then the EKC hypothesis would be confirmed. If sub-indices i and t are not written down, it is assumed that they do not exhibit any kind of effects.

4.1.2. Quadratic specification: Hypothesis 2, fixed effects for individuals $\beta_{0i} = 0$

If the null hypothesis is $\beta_{0i} = 0$, it would express that all income groups have the same intercept. The alternative hypothesis is $\beta_{0i} \neq 0$ that implies that each income group has a different intercept. The fixed effects for individuals on equation (1) allow investigating the intercept variation between countries by income level groups. Notice that sub-index t is not written down since there are not time effects.

4.1.3. Quadratic specification: Hypothesis 3, random effects for individuals $\beta_{1i} = 0$ and $\beta_{2i} = 0$

If the null hypothesis is given by $\beta_{1i} = 0$, then all income groups have the same slope. The alternative hypothesis is $\beta_{1i} \neq 0$ that implies that each income group has a different slope. The random effects for individuals on equation (1) allow investigating the slope variation between countries by income level groups. Notice that sub-index t is not written down since there are not time effects.

4.2. Error-Components Model (ECM)

The equation that represents the ECM is given by:

$$u_{it} = \mu_i + \delta_t + \varepsilon_{it} \qquad (2)$$

where $u_{it} \sim N(0, \sigma^2)$ is the error term of equation (1) representing the unobservable effects on equation (1) that differ among individuals i

and over time t, which is supposed to be *niid* (normal, independent and identically distributed) with zero mean and variance σ^2, μ_i represents the random individual component that change between individuals i, but not over time t, δ_t represents the random time component that change over time, but not between individuals, $\varepsilon_{it} \sim N(0,1)$ is an error term that is considered to be purely random *niid* (standard normal, independent and identically distributed) with zero mean and unit variance. This last term represents the intercept for individual fixed and individual random effects. The cross correlation between μ_i and δ_t is denoted by ρ_{it}, which is expected to be equal to zero if ε_{it} is *niid*. According to Mackinnon et al. (2023), the variance of u_{it} is $\lambda^2 + \omega^2$, and the individual correlation coefficient is $\lambda^2/(\lambda^2 + \omega^2)$. In what follows, for the sake of simplicity, it is written $\theta = \lambda^2/(\lambda^2 + \omega^2)$.

The ECM is aimed to separate from the unobservable effects on equation (1), u_{it}, time and individual components in the intercept at the level of income group. The following expected values are assumed to hold:

$$E(u_{it}\,\varepsilon_{it}) = 0,\ E(\varepsilon_{it}\,\varepsilon_{jt}) = 0,\ E(\varepsilon_{it}\,\varepsilon_{ir}) = 0,\ E(\varepsilon_{it}\,\mu_i) = 0,\ E(\varepsilon_{it}\,\delta_t) = 0$$

In the above expected values, the error in equation (1) and the random error in equation (2) are assumed to be uncorrelated with each other. Furthermore, he assumed that the random error is not autocorrelated with itself ($i \neq j$) and ($t \neq r$), nor with the individual and temporal components

4.2.1. Quadratic specification: Hypothesis 4, random effects for individuals

If the null hypothesis is $\mu_i = \beta_{0i} – \sum_i \beta_{0i}/N = 0$, it expresses the random deviation of the individual intercept by income group with respect to the average of the random individual fixed effects on the intercept are associated with time. If $\beta_{0i} – \sum_i \beta_{0i}/N = 0$, then $\beta_{0i} = \sum_i \beta_{0i}/N$. Here, N stands for the number of individuals and $\sum_i \beta_{0i}/N$ is the average of the random individual fixed effects estimators, β_{0i}, by income group. The alternative hypothesis is $\beta_{0i} \neq \sum_i \beta_{0i}/N$.

4.2.2. Quadratic specification: hypothesis 5, random effects for time

If the null hypothesis is $\delta_t = \beta_{0i} – \sum_t \beta_{0t}/\sqrt{T} – \theta = 0$, it expresses the random deviation of the individual intercept by income group with respect to the average of the random time fixed effects on the intercept considering the correlation coefficient θ, which is associated with individuals. If $\theta = 0$, it will then produce the OLS estimators or the no-effects model. If $\theta = 1$, then it will produce inter-estimator effects. If $\beta_{0i} – \sum_t \beta_{0t}/\sqrt{T} – \theta = 0$, then $\beta_{0i} = \sum_t \beta_{0t}/\sqrt{T} + \theta$. The total number of years is represented by T, $\sqrt{T}$ is a normalization according to Baltagi and Griffin (1983), $\sum_t \beta_{0t}/\sqrt{T}$ is the average of the random time fixed effects estimators, and β_{0i} are the random individual fixed effects estimators by income group. The alternative hypothesis is $\beta_{0i} \neq (\sum_t \beta_{0t}/\sqrt{T}) + \theta$.

5. EMPIRICAL RESULTS

5.1. Unit Root Test

The stationarity of the panel is investigated using several tests. The results from these tests for *logGDPpc* and *logCO2pc* are reported next in Tables 2 and 3, respectively.

Table 2: LLC, HT, BR, IPS and FDF unit root tests, for *logGDPpc* panel composed by countries classified in five income groups, 1970-2016, annual data

Variable	Test	Are panels stationary?	Lag	Statistic	P-value	Options
	LLC	Yes[a]	1	NA	NA	A
				−29.08	0.00	B
				−42.47	0.00	C
				−1.41	0.07	D
	HT	Yes[b]	1	−0.11	0.00	A
				−0.13	0.00	B
				0.98	0.00	C
				0.00	0.00	D
				−0.11	0.00	E
	BR	Yes[c]	1	−18.90	0.00	A
				−22.72	0.00	B
				−2.70	0.00	C
				NA	NA	D
				−18.72	0.00	F
				−10.28	0.00	G
	IPS	Yes[d]	1	−29.60	0.00	A
				−32.17	0.00	B
				NA	NA	D
	FDF	Yes[e]	1	288.34	0.00	A
				288.34	0.00	B
				288.34	0.00	H
				0.00	1.00	D

[a]Adjusted Student's , [b]Rho (ρ) statistic, [c]Lambda (λ), [d]W-t-bar, [e]Inverse Chi-squared ($1/\chi^2$). Source: Own elaboration based on data from the World Bank and using Stata 17 MP. A: No options, B: Include time trend, C: Suppress panel-specific means, D: Subtract cross-sectional means, E: Make small-sample adjustment to T, F: Allow for cross-sectional means, G: Specify lag structure for pre-whitening (1 lag), H: Include drift term. NA: Not available, LLC: Levin-Lin-Chu, HT: Harris-Tzavalis, BR: Breitung, IPS: Im-Pesaran-Shin, FDF: Fisher-type augmented Dickey-Fuller

Table 3: LLC, HT, BR, IPS and FDF unit root tests, for *logCO2pc* panel composed by countries classified in five income groups, 1970-2016, annual data

Variable	Test	Are panels stationary?	Lag	Statistic	P-value	Options
logCO2pc	LLC	Yes[a]	1	−27.34	0.00	A
				−38.91	0.00	B
				−5.92	0.07	C
				NA	NA	D
	HT	Yes[b]	1	−0.05	0.00	A
				−0.05	0.00	B
				0.85	0.00	C
				0.00	0.00	D
				−0.05	0.00	E
	BR	Yes[c]	1	−22.86	0.00	A
				−24.39	0.00	B
				−9.50	0.00	C
				NA	NA	D
				−28.21	0.00	F
				−8.64	0.00	G
	IPS	Yes[d]	1	−27.76	0.00	A
				−29.28	0.00	B
				NA	NA	C
	FDF	Yes[e]	1	288.34	0.00	A
				288.34	0.00	B
				288.34	0.00	H
				0.00	1.00	D

[a]Adjusted student , [b]Rho (ρ) statistic, [c]Lambda (λ), [d]W-t-bar, [e]Inverse Chi-squared ($1/\chi^2$). Source: Own elaboration based on data from the World Bank and Stata 17 MP. A: No options, B: Include time trend, C: Suppress panel-specific means, D: Subtract cross-sectional means, E: Make small-sample adjustment to T, F: Allow for cross-sectional means, G: Specify lag structure for prewhitening (1 lag), H: Include drift term. NA: Not available, LLC: Levin-Lin-Chu, HT: Harris-Tzavalis, BR: Breitung, IPS: Im-Pesaran-Shin, FDF: Fisher-type augmented Dickey-Fuller

All the unit root tests for *logGDPpc* on Table 2 report the presence of a stationary panel. All the above tests were carried out with one lag. The hypotheses of the tests are the following: the null hypothesis is that the panel contains a unit root, and the alternative is that the panel is stationary. For the LLC test, the first two options turn out to be significant at 99% and the third at 90%. The HT tests are significant at 99% in all options. In the BR test, all the options also are significant at 99%, except for option D, which is not available. In the IPS test the first two options are significant at 99%, but option D is not available. Finally, the FDF test in options A, B, and H turns out to be significant at 99%, but in option D the test is not significant. In conclusion, it can be said that the null hypothesis is rejected for all unit root tests reported. It is summarized that the panel for *logGDPpc* is stationary. Table 3 below shows the results of the unit root tests for *logCO2pc*.

All unit root tests for *logCO2pc* on Table 3 represent a stationary panel. All these tests were carried out with one lag. The null hypotheses are that the panel contains a unit root, and the alternatives are that the panel is stationary. For the LLC test, the first two options turn out to be significant at 99% and the third one at 90%. The test HT is significant at 99% in all options. In the BR test, the options A, B, C, F and G also turn out to be significant at 99%, except for option D, which is not available. In the IPS test the first two options turn out to be significant at 99% but option D is not available. Finally, the FDF test in options A, B, and H turns out to be significant at 99%, but in option D the test is not significant. In summary, it can be said that the null hypothesis is rejected in all tests reported on Table 3. Therefore, the panel for *logCO2pc* is stationary.

5.2. Quadratic Specification Results

Next, Table 4 reports the results obtained from the estimation of equation (1). The variable $GDPpc_{it}^2$ presents a perfect collinearity problem with the variable $GDPpc_{it}$. Due to this problem, one of the variables $GDPpc_{it}^2$ or $GDPpc_{it}$ must be eliminated. The variable elimination criterion was based on the best fit for equation (1), either with $GDPpc_{it}^2$ or with $GDPpc_{it}$.[1] The best fit for equation (1) was determined based on the following statistics: Sum of squared errors (SSE) and R_{ajt}^2 (adjusted R^2). Once this criterion was applied, it was found that the variable $GDPpc_{it}$ provides the best fit for equation (1).

5.2.1. Quadratic specification without effects

The estimators corresponding to equation (1) without effects are now described. First, notice that $\beta_1 = 0.93$, which means that per unit change in *GDPpc*, there will be a growth on *CO2pc* emissions of 0.93% for all income groups over the period 1970-2016. The estimator of the constant is $\beta_0 = -6.94$, which means that the regression line has a negative intercept for all income groups in the same period. In what follows, based on the signs of these two estimators, equation (1) under the null and alternative hypotheses 1, 2 and 3 will be examined.

5.2.2. Quadratic specification with individual fixed effects

When different intercepts are allowed for all the income groups, it is known as the individual fixed effects or the covariance model.[2] The estimators corresponding to equation (1) with individual fixed effects are now described. Firstly, $\beta_1 = 0.37$, which means that per unit change in *GDPpc*, there will be an increase in *CO2pc* emissions of 0.37% for all income groups in the period of study. Now, there are different constants values for each income group. For the high income country group the intercept is $\beta_{0i=1} = -1.17$, for the upper middle income group the intercept is given by $\beta_{0i=2} = -2.24$, for the lower middle income group the intercept is $\beta_{0i=3} = -3.07$, and, finally, for in the low income group the origin is $\beta_{0i=4} = -4.38$. The previous results indicate that no income group has a positive intercept, being the high income group the one that presents an estimator closer to zero. The high income group estimator with value −1.17 implies that this group can decrease *CO2pc* emissions with less efficiency. On the other hand, the low income group, on average throughout the analyzed period, is the one that could decrease the *CO2pc* emitted by most by 4.38%. Therefore, it is concluded that the results for this model correspond to the alternative of hypothesis 2, where each income group has a different intercept.

5.2.3. Quadratic specification with individual random effects

The estimators corresponding to equation (1) with individual random effects are next depicted. In this case, $\beta_{1i=1} = 0.55$ for the high income group, it means that an increase in one unit of *GDPpc* will produce an increase of 0.55% in *CO2pc*. For its part, the upper middle income group estimator is $\beta_{1i=2} = 0.47$, which means that an increase in one unit of *GDPpc* will lead to an increase of 0.47% in *CO2pc*. The individual random effects coefficients for the lower middle income group $\beta_{1i=3} = 0.37$ that means that one unit increase in *GDPpc* will produce an increase of 0.37% of *CO2pc*. For the low income group $\beta_{1i=4} = 0.14$, it means that an increase per unit change of *GDPpc* will increase in 0.14% the *CO2pc* emissions. According to these results, the elasticity for the variable *CO2pc* is positive, that is, 0.55, with respect to *GDPpc* for the high-income group, while for the low-income group there is the smallest value of 0.14. These results confirm the alternative of hypothesis 3, where each income group has a different slope. The group of countries that pollutes the most is the high income, and the one that pollutes the less is the low income group. The constant estimate for this specification is −3.01 for all income groups.

The Akaike information criterion yields a value of 3,432.93 for equation (1) without effects. The corresponding value for the

1 Collinearity problems are expected when the same independent variables are used with different exponents. Pirgaip et al. (2023) procedure includes the natural logarithm of the GDP, and then they elevated it to the power of two. The correct procedure seems to be taking the square GDP, and after applying natural logarithm.

2 "The term covariance model is used with reference to the standard analysis of variance layout, which does not consider explicitly any explanatory variables. When the standard analysis of variance effects are combined with those of explanatory variables, the term covariance model is used." Balestra and Krishnakumar (2008).

Table 4: Results of the estimates of equation (1)

Independent variable (-student)	Without effects	Individual fixed effects	Individual random effects
GDPpc	0.93 (67.10)***	0.37 (18.39)***	
High income			0.55 (33.34)***
Upper middle income			0.47 (22.02)***
Lower middle income			0.37 (15.30)***
Low income			0.14 (4.94)***
Constant	−6.94 (−64.42)***		−3.01 (−18.54)***
High income		−1.17 (−5.72)***	
Upper middle income		−2.24 (−14.15)***	
Lower middle income		−3.07 (−21.54)***	
Low income		−4.38 (−35.87)***	
Akaike information criterion	3432.93	2519.49	2679.56
Schwarz information criterion	3443.29	2545.40	2705.47
Root mean squared error	0.89	0.62	0.67
n	1316	1316	1316

***Significant at 99%, *n* is the number of annual observations, 1970-2016, (t-statistics). Source: Own elaboration based on data from the World Bank and Stata 17 MP

individual fixed effects specification is 2,519.49, and for the individual random effects is 2,679.56. For the Schwarz information criterion, the value for equation (1) without effects is 3,443.29. For the individual fixed effects and individual random effects these values are 2,545.40 and 2,705.47, respectively. The Root Mean Squared Error (RMSE) for the regression with no effects is 0.89. For the individual fixed effects and individual random effects the values are 0.62 and 0.67, respectively. The three regressions: individual fixed effects, individual random effects, and no effects were estimated with 1,316 observations. Based on the Akaike and Schwarz statistics, the best model is the one with individual fixed effects, since it presents these statistics with the lowest values. Similarly, the model with the smallest RMSE is the individual fixed effects model. Based on the previous results it can be inferred that the best fit of equation (1) can be achieved with the individual fixed effects model.

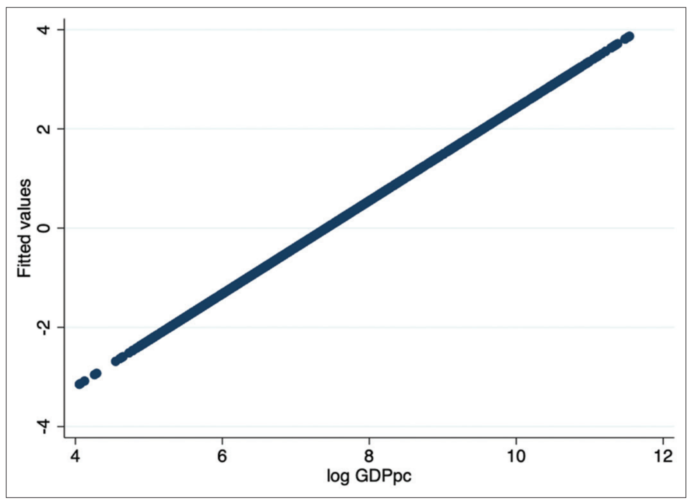
From the previous results, it can be verified that only alternative hypotheses 2 and 3 have a representation in the panel data. Hypothesis 1 is removed in this panel model, which is the one related with the existence on the real world of the EKC. Given the results reported on Table 4, it is concluded that there is not a verification of the EKC hypothesis. It is worth recalling that the estimation of equation (1) leads to a perfect collinearity problem. To estimate equation (1), it is necessary the removal of the quadratic term, under the criteria explained at the beginning of this section. Therefore, the estimated model in Table 4 represents a linear fit using OLS, which is a non-quadratic fit. The linear adjustment made for the estimates reported on Table 4 will be explained through Figures 3-5 in the next section.

5.3. Graphical Analysis

This section presents 3 Figures generated with the statistical software package Stata 17 MP representing the results reported on Table 4. Figure 3, shown below, represents the regression model without effects, equation (1), reported in the first column of Table 4.

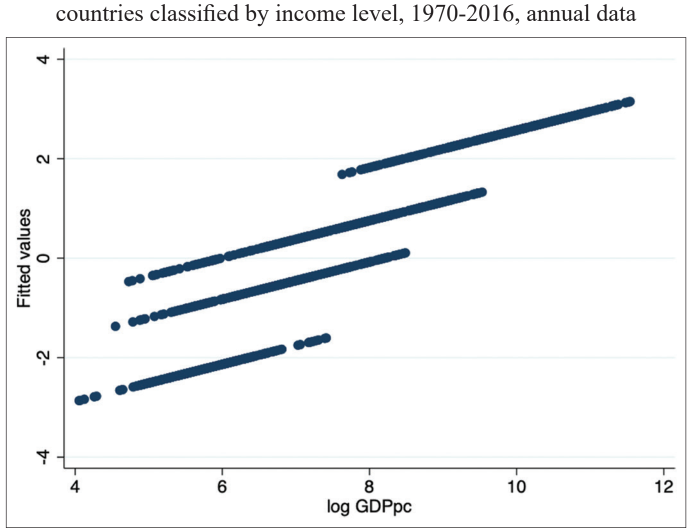
In this case, all coefficients are constant with respect to individuals and time panel dimensions. There is not an intercept differentiation in individuals (i), nor for time (t). Figure 3 shows the visual behavior of the fitted regression line corresponding to the model

Figure 3: Model in equation (1) without effects group of countries classified by income level, 1970-2016, annual data



Source: Own elaboration based on data from the World Bank and using Stata 17 MP

Figure 4: Model in equation (1) with individual fixed effects group of countries classified by income level, 1970-2016, annual data



Source: Own elaboration based on data from the World Bank and using Stata 17 MP reported in the first column of Table 4. A straight line can be seen with no turning point. The expected "U" inverted form corresponding to the theoretical EKC is not displayed. Due to the above, the EKC hypothesis is not verified in this analysis.

Next, Figure 4 shown below presents the model with individual fixed effects for equation (1), reported in the second column of Table 4, for the 4 groups of countries classified by income level.

The linear segments in Figure 4 differentiate four different intercepts, each one corresponding to a distinctive income group. It is observed that there are no income groups with a positive intercept on column 2 of Table 4. To see this, it necessary to draw each line until it reaches the ordinate axis. The constant estimate for the high income group is −1.17. This estimate is significant at the 99% statistic level, with a student *t* distribution value of −5.72. The intercept for the upper middle income group is −2.24 with a statistical significance of 99%. The estimator of the constant for the lower middle income group is −3.07, significant at 99%. The estimator of the constant for the low income group is −4.38, significant at 99%. The group with the highest intercept is determined for that of the high income countries. Finally, the group of countries with the lowest value in the intercept is the low income group. This implies that the high income group is the one that has the highest initial impact on *CO2pc* emissions. It is worth mentioning that there is no evidence at individual level (income group) of the existence of the EKC, since there is no turning point in any of the four groups.

Finally, Figure 5 shows the results of Table 4, column 3 for individual random effects. In this case, each income group has a different slope.

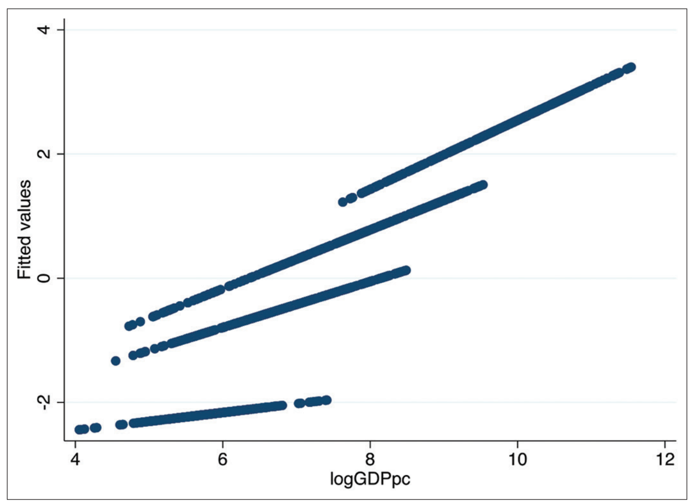
Basically, the individual random effects are obtained by interacting dichotomous variables for each income group with the slopes. Individual random effects identify different slopes for each income country group. The slopes of each line in Figure 5 are reported in Table 4, column 3, as 0.55, 0.47, 0.37 and 0.14 in descending order of income groups, all of them are positive and statistically significant at 99%. It is observed that the low income group has a slope closest to zero. This estimator makes sense, since this group of countries has a very low *GDPpc*, and thus the effect of a 1% increase in *GDPpc* will increase marginally (0.14%) the amount of *CO2pc* emmisions. The high income group has the biggest slope (0.55) among the other income groups. This estimator implies that for 1% that *GDPpc* increases, the *CO2pc* emissions would increase in 0.55%. Therefore, the country group that pollutes the most is the one pertaining to the richer countries. As in the previous Figures 3-5 has no indication of a turning point to mark an inverted "U" form to confirm the EKC hypothesis, at least for the countries and years considered in this panel model.

5.4. Error-Components Model (ECM) Results

Next, in Table 5, equation (2) estimates are reported. Equation (2) is an ECM that uses as the dependent variable the residuals of equation (1).

According to the ECM results reported in Table 5, for the random component for individual fixed effects, in column 1, the intercept estimator for this column is ε_{it} =−2.71. This estimator indicates that there is a negative relationship between the residuals of equation (1) and the error of equation (2). The corresponding slope is μ_i = 0.37 of all unobservable effects on equation (1), which change among individuals but no over time. In this same column are reported the results for the individual intercepts μ_t for

Figure 5: Model in equation (1) individual random effects group of countries classified by income level, 1970-2016, annual data



Source: Own elaboration based on data from the World Bank and Stata 17 MP

Table 5: Results of the estimates of equation (2), error-components model

Independent variable (*t*-student)	Dependent variable equation (1) errors	
	Individual fixed effects 1970-2016	Individual random effects 1970-2016
Error components		
Slope	0.37 (18.39)***	0.38 (18.39)***
Constant	−2.71 (−17.64)***	−2.82 (−10.39)***
High income	1.54 (26.78)***	1.54 (27.00)***
Upper middle income	0.47 (15.80)***	0.48 (16.00)***
Lower middle income	−0.35 (−10.62)***	−0.35 (−10.45)***
Low income	−1.66 (−35.50)***	−1.65 (−35.25)***
Akaike information criterion	2519.49	−6932.47
Schwarz information criterion	2545.40	−6906.56
Sum of squared residuals	518.73	0.39
n	1316	1316

***Significant at 99%, *n* is the number of annual observations, 1970-2016, (t-statistics). Source: Own elaboration based on data from the World Bank and Stata 17 MP each income group, which represents the unobservable effects on equation (1) that change with time, but not over individuals. The high income group displays an estimator of 1.54, the upper middle income group is 0.47, for the lower middle income group −0.35, and for the low income group is −1.66. All the estimators for the four income groups are statistically significant at 99%.

Regarding the ECM results reported on Table 5, for the random component for individual random effects, in column 2, the coefficient of the estimator corresponding to the intercept is ε_{it} = −2.82. This coefficient indicates that there is a negative initial value or intercept of the line fitted by the panel model between the residuals from equation (1) and the errors of equation (2). The slope estimator for this column is $\delta_t = 0.38$. This coefficient indicates that there is a positive relationship between a time trend and the residuals from equation (1). In this same column there is also reported the individual random effects of the income groups δ_i that change between individuals, but not over time. For the high income group the corresponding estimate is 1.54, for the upper middle income group is 0.48, for the lower middle income group is −0.35 and for the low income group is −1.65. All the estimators for the four income groups are statistically significant at 99%.

When comparing the results on Table 5 for columns 1 and 2, it can be noticed that results appear to indicate that there are no major differences, and for this reason there is a systematic behavior on the residuals of equation (1). This systematicity sheds some light on the results reported on Table 4. The results that appear in Table 4 in the second column indicate that all income groups have a negative intercept. These results on Table 4 suggest which income group contributes the less to pollute, although with negative estimators. However, these signs are further clarified with the results from the ECM, which indicates that the income groups that effectively contribute the most in emissions, with positive estimates, are the high income and the upper middle income groups.

Table 5 displays the results for the ECM. The constant for the individual fixed effects model common intercept was found to be −2.71, reported in the first column of Table 5. This indicates a negative relationship of the common residuals with time. A similar result is obtained for the individual random effects. In this case, a value of −2.82 is reported in the second column of Table 5. These estimates −2.71 and −2.82 indicate that as more time passes, the equation (1) error will decrease; in the long run a decrease in pollution is expected. When comparing the results of columns 1 and 2, it can be verified that their estimates are similar. Thus, the estimates are systematic across fixed and random effects. The group of countries that pollute the most are those with positive estimators, namely the high income (with an estimator of 1.54 in both columns) and upper middle income (with an estimator of 0.47 and 0.48 in columns one and two, respectively). Notice that the individual fixed effects on Tables 4 and 5 are the same. They take the common constant from Table 5, column 1, with a value -2.71, and added it to the high income constant 1.54 from the same Table 5, it is obtained that the high income constant from Table 4, column 2, as −1.17. In a similar manner, for the rest of income groups: −2.71 + 0.47 = −2.24 for the upper middle income, −2.71 −0.35 = −3.07 for the lower middle income, and −2.71-1.66=−4.38 for the low income group. The sum up of the individual fixed effects estimates for each income group is zero (1.54 + 0.47-0.35-1.66 = 0). Hence, the income specific effects cancel each other out and eliminating their time effect. Therefore, the within estimate −2.71 represents the income growth without a time bias. With only one intercept for all income groups, then there is only one regression line.

To select the best ECM specification from Table 5 is necessary to perform a Hausman test. This test would help to decide which component, individual fixed effects or individual random effects offer the best fit.

5.5. Hausman Test Including ECM

To help in decide which component model from Table 5 offers the best statistic fit, the Hausman's (1978) test is used. This test is based on the Chi-square distribution (χ^2), which determines whether the differences are systematic and significant between the estimates of the fixed and random effects for the ECM. This test is mainly used for two reasons: The first is to know which estimator component is more consistent, and the second is to know if the component is relevant or not. The hypotheses for the Hausman test is as follows: The null hypothesis assumes that the individual random effects model is the one that best explains the relationship between the dependent variable and the explanatory variables. Therefore, the alternative hypothesis is that the best model is individual fixed effects.

If the value of the Hausman test is <0.05 ($P < 0.05$), the null hypothesis of equality at 95% confidence is rejected, and the individual fixed effects model presents the best fit. On the contrary, if $P > 0.05$, the null hypothesis of equality of estimates must be accepted and the most efficient estimator comes from the individual random effects specification. Likewise, if the $P > 0.05$, then it must be assumed with 95% confidence that the estimators in the individual fixed effects model is not the best model. Next, Table 6 shows the results from the Hausman test applied to ECM results reported on Table 4.

As reported on Table 6, the slope coefficients for equation (2) for individual fixed effects and individual random effects are similar, 0.37 and 0.38 respectively, with a difference of about −0.01. The degrees of freedom of the statistic $\chi^2(1)$ are the range of the difference in the variance matrices. When the difference is a positive definite matrix, the number of common coefficients of the panels compared is equal to 24.81. As a result of the application

Table 6: Results of the estimates of equation (2)

Variable	(*b*) fixed	(*B*) random	(*b–B*) difference	$\sqrt{\text{diag}(V_b - V_B)}$ SE
$logGDP_{pc}$	0.37	0.38	−0.01	0.00

Hausman test for individual fixed effects and individual random effects. Country groups by income level, 1970-2016, annual observations. Null hypothesis: $E(\varepsilon | X) = 0$, alternative hypothesis: $E(\varepsilon | X) \neq 0$, b=consistent under the null hypothesis and alternative hypothesis, obtained from column one on [Table 5], slope estimator. B=inconsistent under the alternative hypothesis, efficient under the null hypothesis; obtained from column two on [Table 5], slope estimator. Null hypothesis test: Difference in coefficients not systematic $\chi^2(1) = (b-B)'(V_b - V_B)^{-1}(b-B) = 24.81$. Prob > χ^2=0.00. In the Hausman test, if the probability > χ^2 is>0.05, then the null hypothesis is accepted. If the opposite happens, probability > χ^2 is<0.05, then the null hypothesis is rejected, which means that the individual random effects is less reliable. Source: Own elaboration based on data from the World Bank and Stata 17 MP. SE: Standard error of the Hausman test, it is obtained that Prob> χ^2 is zero (<0.05), for which the null hypothesis of model equality is rejected at a 95% of statistic confidence. Thus, it is concluded that the best model, according to Hausman test, is the one corresponding to the individual fixed effects specification.

6. CONCLUSION

This investigation has provided descriptive statistics, graphical analysis, and econometric estimates that help to better understand the impact of income measured by *GDPpc* on *CO2pc* emissions. The emission of this gas is considered one of the main causes of global warming and a cause for environmental degradation. For these reasons, lowering *CO2pc* emissions should be a priority for governments. There are agreements such as the 1997 Kyoto protocol which commits industrialized countries to limit and reduce greenhouse gas (GHG) emissions in accordance with common individual goals (United Nations Climate Change, 2005). For its part, the Conference of the Parties (COP) is a dialogue panel with a total of 197 nations and territories responsible for supervising and examining the application of the United Nations Framework Convention on Climate Change. This convention requires each Party to publish a nationally determined contribution action plan, which will reflect its measures to meet the objective of the Framework Convention to reduce greenhouse gas emissions (World Meteorological Organization, 2022). In turn, it also analyzes the reduction of greenhouse gas emissions to limit global warming to a maximum increase of two degrees Celsius, for the period between 2035 and 2050. The analysis from the present research seems to indicate, that the actions taken during the meetings do not seem to have a real impact on pollution reduction.

From the analysis of Table 4 results, it can be verified that the only alternative hypotheses 2 and 3 have a representation in the panel data. Hypothesis 1 is not verified in this panel model; being hypothesis 1 the one related with the existence of the EKC. Given the results reported on Tables 4 and 5, it is suggested that there is not a theoretical or an empirical EKC. It is worth mentioning that the slopes of the income groups analyzed in this document do not change from positive to negative, by reaching a turning point that could allow an inverted "U" EKC shape. Figures 3-5 show increasing levels of pollution, where the high income group has a higher participation. Moreover, the estimation of equation (1) reveals that the quadratic coefficient of *GDPpc* generates a collinearity problem. To avoid this problem, it was determined that the best fit of equation (1) is linear, over the quadratic fit. Therefore, equation (1) is estimated with a linear regression based on a double logarithm functional form. Through the visualization of Figures 3-5 of the panel regression estimates of equation (1), it was found that there is no evidence to verify the EKC hypothesis.

The ECM was implemented to separate the time effect measured by a common constant from time effects of each income group. Also, the ECM was used to investigate the income group estimates with negative sign reported on Table 4, and to conclusively know which income group pollutes the most. The ECM results indicate that the income groups that effectively contribute the most in polluting, with positive estimates, are the high income and the upper middle income groups. These results suggest that at present the predominant technological level, of each of these two income groups operates by burning fossil fuels.

The Hausman test was applied to determine parametrically which ECM specification is better, the individual fixed effects or the individual random effects. The Hausman test determined that the best specification is the individual fixed effects. Therefore, it is correct the application of the ECM to the individual fixed effects (Table 4, column 2), which is the one that offers the best statistic fit.

From the results reported in this document, it can be inferred that the hypothesis of a theoretical EKC associated with an optimal income level and an advance technology based on clean and renewable energies has not yet been reached, at least for the panel data and studied and the period analyzed; 28 countries and 46 years. From Figures 4 and 5, the high income group is the closer to a turning point, with respect to the other income groups. Probably this result is due to the technology efficiency level used by this income group. Consider Figure 2 where the general trend of *CO2pc* is descending for the high income group, although with high levels of air pollution. It seems that the newest and efficient technology is used in the high income group, but still, it relies in burning fossil fuels. Apparently, the turning point from the EKC hypothesis that is reached when the technology shifts from burning fossil fuels towards clean energies has not yet been reached. In other words, it is possible that, in the future, the theory of the EKC could be verified since the evidence shows that there is a positive slope in the data, and the high income group is the closer to reach a turning point. If an optimal income level is reached in a turning point, then it is possible that the degradation of the environment would decline.

Finally, in the future research agenda on the link between CO_2 and GDP, other factors that could affect the EKC will be taken into account, such as technological development, investment in research, emissions by sector, availability of resources natural, pro-environmental public policies, the speed of the energy transition, etc.

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APPENDICES

Appendix 1. Data sources and units

Table A1: Data sources and units

Data identifier	Description	Frequency	Available period	Source	Units
PIBpc	Per capita gross domestic product	Annual	1960-2019	World Bank	USD at current prices per capita
CO2pc	Carbon dioxide emissions per capita	Annual	1960-2016	World Bank	metric tons per capita

Appendix 2. Groups income countries classification in High, Upper Middle, Lower Middle, and Low Income

Table A2: Income groups

Low income countries	Lower middle income countries	Upper middle income	High income
Congo, Democratic Republic	Bangladeshi	Argentina	Canada
Niger	Belize	Brazil	United Kingdom
Rwanda	Honduras	China	Japan
Sudan	Kiribati	Guatemala	France
Sierra Leone	Nigeria	Mexico	Norway
Togo	Nicaragua	Peru	Qatar
Uganda	Salvador	Thailand	United States

Source: Own elaboration with data from the World Bank

The Table above shows the groups of countries classified by income level (low, low middle, high middle, and high). The presentation of this Table includes by names the countries that make up each of the income groups. In this document, it was considered to perform the analysis of these income groups through a balanced panel model. Therefore, for each income group, seven countries were considered, where each of them will present complete data for the period from 1970 to 2016, with annual observations for both *GPDpc* and *CO2pc*.

Table A3: Country income group thresholds

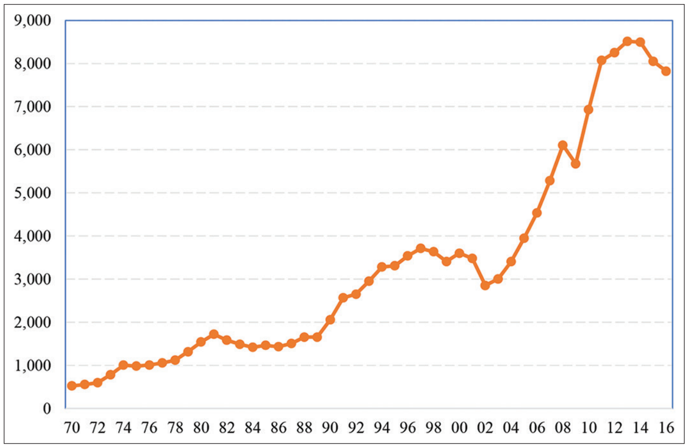
Threshold	*GDPpc* in USD
Low income country	1,025 or less
Lower middle income country	Between 1,026 and 3,995
Upper middle income country	Between 3,996 and 12,375
High income country	More than 12,375

Source: World Bank

Table A3 above explains the cut-off points for classify the different income groups measured in USD. These cut-off points follow the World Bank methodology, which is used to determine the classification by income level of different countries. This classification belongs to the period 2019-2020. The World Bank determines this classification considering the *GDPpc* of each country, which can change according to economic growth, inflation, exchange rates and population. The classification threshold is adjusted annually for inflation using the Special Drawing Rights (SDR) deflator.

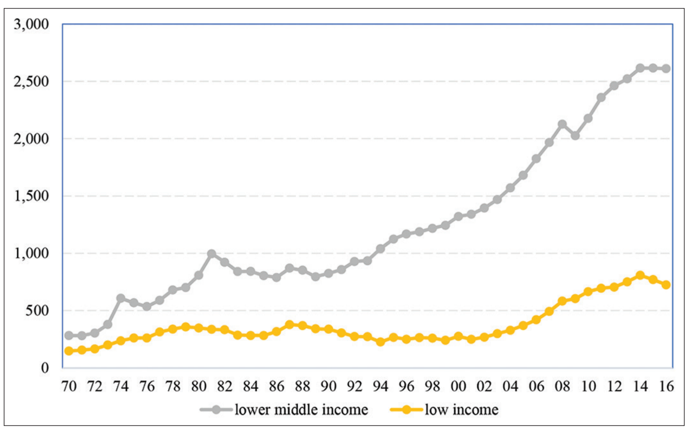
Appendix 3. Complementary Figures

Figure AG1: Upper middle income group, 1970-2016 annual. Gross Domestic Product per capita in USD



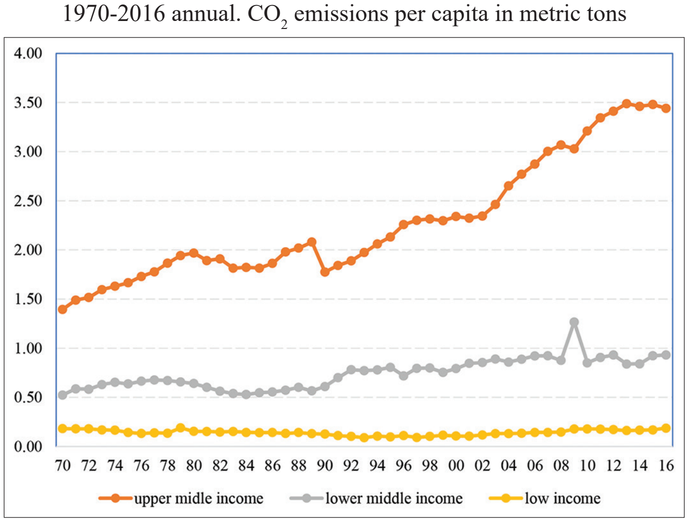
Source: Own elaboration based on data from the World Bank

Figure AG2: Low and lower middle income groups, 1970-2016 annual. Gross Domestic Product per capita in USD



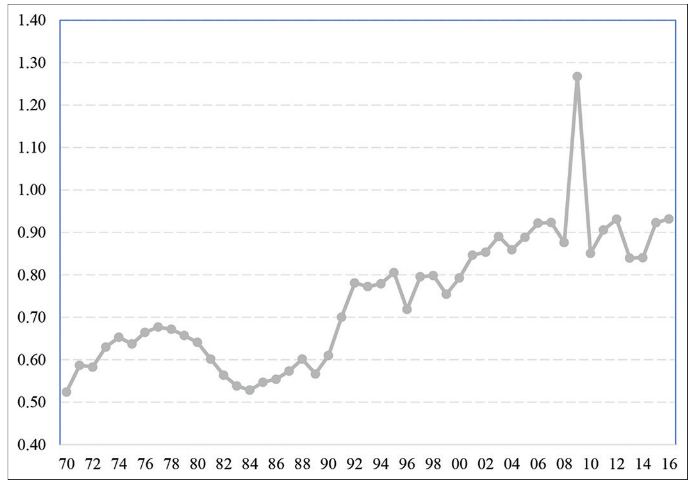
Source: Own elaboration based on data from the World Bank

Figure AG3: Low, lower middle and upper middle income groups, 1970-2016 annual. CO_2 emissions per capita in metric tons



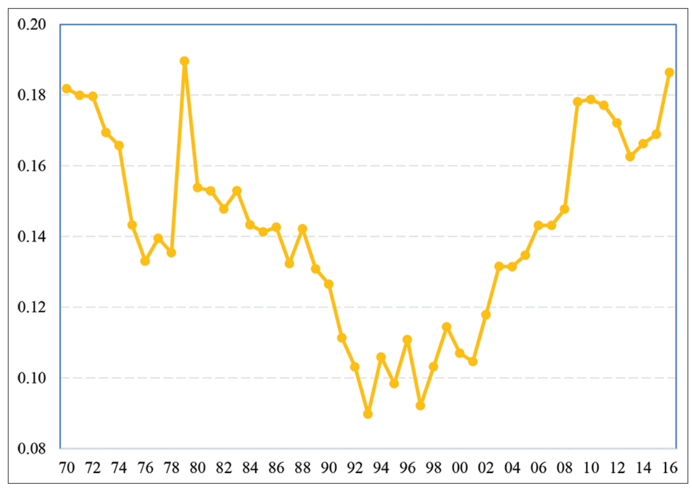
Source: Own elaboration based on data from the World Bank

Figure AG4: Lower middle income group, 1970-2016 annual, CO_2 emissions per capita in metric tons



Source: Own elaboration based on data from the World Bank

Figure AG5: Low income group, 1970-2016 annual. CO_2 emissions per capita in metric tons



Source: Own elaboration based on data from the World Bank