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Is the Environmental Kuznets Curve Universal? Evidence from Pollution and Resource-Based Environmental Indicators in 149 Countries, 1995–2019

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ABSTRACT

The Environmental Kuznets Curve (EKC) hypothesis suggests that environmental degradation initially worsens with increase in income before declining after a country reaches a certain income threshold. This framework has been tested extensively for carbon dioxide emissions and local pollutants, but little is known about whether it generalizes to the broader range of environmental pressures that arise from economic expansion. Using a panel of 149 countries over 1995–2019 (3,725 country-year observations), this paper estimates the EKC across six environmental indicators spanning both pollution-based degradation (CO_2, CH_4, N_2O, PM2.5) and resource-based degradation (natural resource depletion, forest damage). The analysis employs fixed-effects (FE) models with country-clustered standard errors, along with the Lind-Mehlum U-test to validate the income threshold. The FE estimates, cross-checked against System GMM and Pooled Mean Group dynamic-panel estimators, show that the EKC is not a single, universal relationship. An inverted-U pattern holds for all four pollution-based indicators in the global sample, but resource-based degradation displays no such pattern: natural resource depletion does not show significant relationship with income, while forest depletion instead worsens with increase in income. Income turning points also vary sharply between developed and developing countries (G-77 or Global South) and across regional subsampling. Among G-77 developing countries, the income threshold where per-capita carbon emissions start decreasing is estimated at approximately $72,300, above the income of every country in the sample and showing no evidence of genuine income turning point, while the threshold for reducing PM2.5 exposure appears valid and between $1770 and $2,700, within reach for most low-income economies today. On the other hand, high-income OECD countries show no significant EKC patterns at all. These findings indicate that the "grow now, clean up later" logic highlighted in much development policy applies, at best, to local air pollutants but not to greenhouse gas emissions or natural resource use, where developing countries cannot expect income growth alone to deliver environmental improvement within any realistic time horizon.

Keywords: Environmental Kuznets Curve, economic development, environmental degradation, natural resource depletion; sustainable development, pollution.

1. Introduction

Development policy in most countries, particularly low and middle-income countries, often rests, at least implicitly, on the idea that economic growth is a precondition for environmental improvement, not an obstacle to it. This prediction is captured in economics and environmental literature as the Environmental Kuznets Curve (EKC), which suggests that environmental degradation rises in the early stages of economic development, often led by agrarian sector and followed by industrialization, then declines at a later stage of development when income crosses a certain threshold. The improvements in environmental conditions after reaching the income threshold often reflect cleaner technology, stronger institutions, and a shift toward less pollution-intensive production that change with economic growth (Grossman & Krueger, 1991, 1995; Panayotou, 1993; Selden & Song, 1994; Shafik, 1994).

Literature consistently reports that the EKC inverted-U pattern is fragile as it holds for some pollutants and not others, remains valid in some country samples and not others, and is sensitive to functional form and estimation technique (Dinda, 2004; Stern, 2004; Dasgupta et al., 2002). One big problem remains the complexity of environmental degradation often reflected in its own definition spanning atmospheric pollution, ecological pressure, biodiversity loss, and disturbances in the hydrosphere.

In this paper, I argue that a large part of this fragility is linked to the definitional restriction of environmental degradation. Most EKC studies test a single environmental indicator, particularly and overwhelmingly carbon dioxide emissions and local pollutants, and then generalize the result, implicitly or explicitly, to "the environment" as a whole. For instance, carbon emissions only

capture a specific dimension of environmental pressure and remain not necessarily a representative one despite their dominance among greenhouse gas emissions. However, while income may be significantly linked to carbon emissions and particulate matter, other environmental outcomes do not always change with income alone. Pollutants such as nitrogen oxide and methane emissions are largely influenced by structural and geographic characteristics whereas natural resource depletion and forest loss operate through a different mechanism, including direct extraction and land-use conversion, that do not necessarily respond to income in the same way.

Resource-based degradation may in fact worsen as economic expansion demands more land, timber, and raw material inputs regardless of income level. A policy conclusion drawn from carbon emissions alone and in certain circumstances local pollutants, and generalized to the broad environmental conditions, may be misleading. By suggesting that growth will eventually solve environmental degradation, the EKC hypothesis raises important concerns linked to its universality, particularly for many pollutants and more importantly to resource-based degradation, where the underlying economic mechanism is not the one the EKC was initially built to describe.

This paper addresses this gap directly by estimating a parsimonious income-centered EKC relationship across six environmental indicators, including pollution-based and resource-based degradation and further examine whether the turning points of confirmed EKC patterns remain genuinely valid and economically plausible. To the best of my knowledge, there are no EKC studies that test multiple environmental indicators within a single, consistently specified panel framework. This limited comprehensive study makes it difficult for the existing literature to say with confidence which environmental problems follow the EKC logic, and which do not. Closing this gap remains the paper's central contribution.

A second contribution remains attached to the policy relevance of the income turning points. Even where an EKC relationship holds, its policy relevance depends entirely on where the income turning point falls relative to the country's current income levels. A statistically significant EKC pattern estimated from a global sample dominated by high-income observations can imply a turning point that no developing country is able to reach within the foreseeable future. This often suggests that, in many cases, the EKC is only true in a purely mathematical sense but irrelevant as a guide to what developing countries should expect from growth over any realistic planning horizon. Each of the estimated turning points are formally tested for validity using the Lind and Mehlum (2010) U-test, a test many EKC studies omit, and which remains essential for distinguishing a genuine inverted-U from a monotonic relationship that happens to fit a quadratic functional form over a limited income range.

The study motivates real caution about how the EKC hypothesis is used in development policy discourse. I find that the inverted-U shaped pattern holds for all four pollution-based indicators in the global sample, with income turning points ranging from roughly $2,700 for PM2.5 to $21,300 for per-capita CO_2 emissions. But this global pattern masks important divergence between developed and developing countries. In the G-77 sample for instance, the turning point for per-capita CO_2 emissions rises to approximately $72,300, which is far above the income of every developing country in the sample and not validated by the Lind-Mehlum test, demonstrating that the EKC curve in this context is not genuinely valid within any G-77 income range. The same is true, to a lesser degree, for methane emissions. PM2.5, on the other hand, shows a turning point under $2,000 in the G-77 sample, capturing a threshold that many developing countries have already reached. This suggests that unlike global GHG emissions, local air quality can genuinely improve with modest income growth. Resource-based degradation shows no EKC pattern in any

sample. These findings suggest that the EKC is not one relationship but several, and that treating it as a single, general-purpose justification for growth-first environmental policy is not supported by the data.

This study contributes to the literature in four ways. First, it simultaneously evaluates pollution-based and resource-based environmental indicators within a unified EKC framework. Second, it examines a broad global panel of 149 countries covering 1995–2019. Third, it validates estimated turning points using the Lind-Mehlum test rather than relying solely on coefficient signs. Finally, it demonstrates that EKC conclusions are highly dependent on the environmental indicator examined and should not be generalized to the broader environmental degradation.

The remainder of the paper is organized as follows. Section 2 reviews the EKC literature, with particular attention to the multi-pollutant and developing-country evidence most relevant to the paper's contribution. Section 3 describes the data, sample, and diagnostic tests for panel stationarity and cointegration. Section 4 presents the empirical strategy. Section 5 reports results, including turning-point estimates and their validation across income groups. Section 6 discusses policy implications, and Section 7 concludes.

2. Literature Review

The Environmental Kuznets Curve (EKC) hypothesis was conceived after Simon Kuznets provided the premises of an inverted U-shaped relationship between inequality and income levels (Kuznets, 2019). This hypothesis is expanded to capture the relationship between environmental degradation and economic development, described today as the Environmental Kuznets Curve (EKC).

The claim that economic growth would foster environmental degradation started to be empirically investigated in the early 1990s by numerous scholars, including Grossman & Krueger (1991; 1995), Shafik (1994), Panayotou (1997) and Stern et al. (1996). Grossman & Krueger (1991)'s cross-sectional countries analysis of local air quality measures in North America have laid out the foundations for the Environmental Kuznets Curve (EKC). Drawing an analogy to Kuznets' income-inequality relationship, the Environmental Kuznets Curve suggests an inverted U-shaped relationship between environmental degradation and economic development.

In fact, at the initial stage of development, environmental degradation becomes inevitable because of the dependence on the primary sector of production such as agriculture and extraction along with the limited income and technology that shape production processes. Degradation intensifies with income as the country industrializes until peaking at a certain income level. But at a higher income level, the country starts employing cleaner resources, presumably due to technological change, demand for cleaner products increases, redirecting production to become more sustainable.

Early EKC empirical evidence centered on local air pollutants. Grossman and Krueger (1991) examined the environmental implications of the North American Free Trade Agreement (NAFTA) and found inverted U-shaped relationships for sulfur dioxide and dark matter suspended in the air (smoke) across 42 countries, with income turning points estimated between 4000 and 5000 US (1985 USD). Their results further suggest that concentration of suspended particulate matter decreases even at lower income levels. Panayotou (1997) found evidence of the EKC for ambient sulfur dioxide (SO2) levels although their EKC decomposition model revealed that institutional quality and environmental policy can hinder environmental at low-income levels and speed environmental improvement processes at higher income levels.

Shafik & Bandyopadhyay (1992) extended this inquiry by analyzing the EKC relationship using different levels of income and multiple indicators of environmental degradation, including deforestation, access to clean water, river quality, and air pollution. Their findings revealed that income has a significant and relatively consistent effect across many environmental indicators, although the direction and magnitude of this relationship vary by pollutant. They found weak evidence of improvement in river quality and mixed evidence for air quality.

Shafik (1994) further expanded this question by estimating the EKC for ten indicators using three different functional forms. Their results suggest that local air pollutants followed the path of the EKC with turning points generally occurring at relatively low-income levels, estimated between 300 and 4000 US dollars. Conversely, they found that both municipal waste and carbon dioxide emissions per capita were associated with higher income levels while deforestation was found to have no relationship with income.

Another recent EKC empirical contribution comes from Polat & Çil (2025), who tested the EKC hypothesis in 39 countries between 1993 and 2018 using fixed-effects estimation. Rather than using GDP per capita, they employed the Human Development Index as the main independent variable, methane and carbon emissions as environmental outcomes. Their findings suggest that broader measures of development, particularly human development and environmental education, may be more informative than income alone in explaining environmental outcomes. They argue that improvement in HDI is stronger than compromise on growth to mitigate environmental degradation, suggesting that accelerating qualitative progress such as HDI and environmental education, as well as improving market regulations and incentives help achieve sustainability.

One of the most common and substantive EKC critiques is that it is highly pollutant specific. The EKC is often applied to certain pollutants and does not always yield the same results

when applied to others and does not consistently apply in distinct economic and institutional contexts, making scholars cautious about its application (Stern, 2004). For these reasons, literature records mixed evidence about the inverted U-shaped relationship between economic development and environmental degradation (Stern, 2004; Chu, 2021).

Although the evidence found by Grossman & Kruger (1991) suggested that economic growth reduces pollution, it is worth noting that their analysis has been restricted to a very few air pollutants, excluding critical pollutants such as carbon emissions. Hettige et al. (2019) tested the EKC by measuring the effect of income growth on three different pollutants, including share of industry in national output, industrial output, and on "end of pipe" pollution intensities. Their results suggest that industry share of national output follows the EKC whereas the other two pollutants and the combined model do not follow the EKC hypothesis. As a result, evidence supporting the EKC for one pollutant does not imply that environmental improvement occurs uniformly across all dimensions of environmental quality.

This critique also applies in the context of the conservation of biodiversity or resource use, pointing out important limitations that require more attention regarding the EKC hypothesis (Stern, 2004; Mills & Waite, 2009). A more systematic reassessment arises from the work of Dasgupta et al. (2002) whose work illustrates that EKC patterns often hold in situations where pollutants have visible and immediate costs. Their study reveals that global pollutants and natural resource depletion rarely follow EKC patterns, in addition to unclear turning points.

The reliance on economic growth to improve environmental outcomes has also drawn attention. In fact, market liberals often argue that environmental degradation is caused by the lack of economic growth and poverty, insinuating that the solution to environmental problems resides in income growth (Clapp & Dauvergne, 2011). Although many scholars, including Tamazian et.

al. (2009), found evidence that both economic and financial expansion reduces environmental degradation in emerging countries such as BRIC's (Brazil, Russia, India, and China) economies, the assumption that growth alone will automatically lead to improvements in environmental outcomes appears misleading.

Stern et al. (1996) argues that considering growth maximization as the only solution to environmental degradation can be a problem, especially when not accounting for environmental effects on the economy, particularly in developing countries. In this context, Stern (2004) adds that sometimes developing countries have better environmental performance than wealthy countries, questioning the income threshold condition before environmental improvement. The distinction between developed and developing countries remains critical to capturing whether EKC follows the same patterns and is consistent across development groups.

The mixed evidence from the EKC highlights the variation of the applicability of the EKC hypothesis in different geographic, economic, and institutional contexts. Growth alone cannot help achieve environmental sustainability, particularly in countries with weak institutions and highly dependent on natural resources (Ssekibaala et al., 2022). In many of the critiques, policy adjustments remain of high importance to attain a sustainable global economy (Stern et al., 1996; Wang & Wheeler, 2003).

Hypothesis

My study suggests that generally, economic development exhibits a nonlinear relationship with environmental degradation. However, the strength, direction of the coefficient and the existence of the EKC vary across environmental indicators. The EKC relationship is expected to hold for emissions-based indicators and partial, weaker or non-existent for resource-based indicators. Natural resource depletion continues to increase even at higher stage of development. The study,

therefore, highlights a clear distinction between resource-based and pollution-based income-environment relationships.

For pollution-based degradation:

$$H1a: \beta_1 > 0 \text{ and } \beta_2 < 0$$

For resource-based degradation:

$$H1b: \beta_1 > 0 \text{ and } \beta_2 = 0$$

Where β_1 captures the linear effect of income at the initial level of environmental degradation, while β_2 captures the nonlinear (quadratic) effect of income on environmental degradation at higher income levels, following Grossman & Krueger (1991; 1995). The alternative hypotheses presented in this study contend that the EKC holds for selected environmental outcomes, rather than universally.

3. Data and Methodology

3.1.Research Design

The study uses secondary country-level data and does not involve direct interaction with human participants. Data are obtained from publicly available international databases, including the World Bank's World Development Indicators and the Penn world Table (PWT 11.0) which I used to construct a harmonized global panel dataset because of their level of integrity, transparency and high standards of reproducibility. The World Bank World Development Indicators (WDI) and the Penn World Table (PWT 11.0) provide extensive cross-country information on economic performance and various dimensions of environmental outcomes needed in this study.

The study covers the period ranging from 1995 to 2019, which captures significant economic and environmental transformations, particularly in developing countries. The mid-1990s

marked a major shift in international cooperation regarding environmental governance, especially after the 1992 Rio conference. This period also reflects the broader economic and political transitions following the end of the Cold War and the access to sovereignty of many countries, which reshaped development trajectories and global dynamics around the world. I have excluded observations earlier than 1995 from the analysis because of the higher number of missing values in the data, particularly for the newly independent countries and other countries that faced longer periods of war and political instability.

The year 2019 is deliberately chosen as the endpoint of the sample to avoid distortions and biases created by the COVID-19 pandemic. Notably, the 2019 pandemic was identified in December 2019 in China but was declared a pandemic in March 2020. This global shock has significantly disrupted economic activity and environmental outcomes, with most of the effect materializing from 2020 onward.

The unit of analysis in this study is country-year observations, consisting of country-level observations over multiple years. The final dataset constitutes a strongly balanced panel covering 25 years, spanning from 1995 to 2019, which provides sufficient variations across both countries and time for a comprehensive analysis. This panel structure (25 years and 149 countries in total) allows the analysis to control for unobserved country-specific heterogeneity and regional differences and identify the long-run economy-environment relationship.

Following data cleaning and the removal of observations with substantial missing values, the final sample consists of approximately 149 countries and 3,725 country-year observations. The selection of countries was primarily based on data availability and consistency across the study period, particularly for the environmental outcome variables and income indicators. The sample

includes both developed and developing countries to enable comparisons across different stages of economic development.

The outcome variables comprise multiple environmental indicators spanning both pollution-based and resource-based degradation. Specifically, dependent variables are carbon emissions (both per capita and total emissions), total nitrous oxide emissions, total methane emissions. PM2.5 exposure, natural resource depletion and forest depletion. The independent variables are the linear GDP per capita and the quadratic GDP per capita, employed to capture the functional EKC non-linear relationship. All FE models include year fixed-effects (from 1996 to 2019) to absorb common time-varying shocks with 1995 as the base year (omitted).

3.2. Econometric Specification

The study adopts a quantitative panel data approach and seeks to identify broad reduced-form income-environment relationships across indicators rather than estimate the independent effect of income conditional on a large set of covariates. The empirical strategy is grounded in the Environmental Kuznets Curve (EKC) framework, using parsimonious income-centered EKC models, primarily estimated through fixed effects analysis with clustered standard errors at country level. The FE analysis is complemented with dynamic panel estimators, including the system-GMM and PMG for robustness.

The baseline model is employed to globally test the EKC hypothesis. This framework posits that environmental degradation initially increases with GDP per capita and eventually decreases after GDP per capita rises further or reaches a certain threshold.

A. Fixed Effect Techniques

The EKC functional model for country i at time t, while controlling for unobserved country and time specific heterogeneity, is expressed as:

$$\mathrm{E}_{it} = \beta_0 + \beta_1 y_{it} + \beta_2 \, {y_{it}}^2 + \mu_i + \lambda_t + \epsilon_{it} \qquad (1)$$

After the log transformation, the model becomes:

$$\ln E_{it} = \beta_0 + \beta_1 \ln y_{it} + \beta_2 (\ln y_{it})^2 + \mu_i + \lambda_t + \varepsilon_{it} \qquad (2)$$

where $\ln E_{it}$ is the natural log of an environmental degradation indicator (CO_2, CH_4, N_2O, PM2.5, forest depletion or natural resource depletion); $\ln y_{it}$ is log income per capita, $(\ln y_{it})^2$ is its square capturing the nonlinear EKC relationship. β_0 is the intercept, representing the baseline level of environmental degradation when income is zero. β_1 is the linear coefficient for income at the initial phase of economic development, β_2 is the quadratic coefficient for income; μ_i represents country fixed effects absorbing time-invariant unobserved heterogeneity; λ_t captures year fixed effects absorbing common time trends; and ε_{it} is the idiosyncratic error term. The time index is captured by t and country index is captured by i.

To address potential endogeneity and dynamic persistence, system GMM is employed using two-step robust estimator with collapsed instruments to improve efficiency and limit instrument proliferation (Bond et al., 2001; Xaisongkham & Liu, 2024).

Additionally, the PMG is estimated based on the error-correction representation of the Autoregressive distributed lag to capture the long-run equilibrium relationship between economic development and environmental degradation.

B. EKC Conditions, Marginal Effect and Income Turning Points

For the EKC to be confirmed, the following conditions must hold:

$$\beta_1 > 0 \; and \; \beta_2 < 0$$

The marginal effect of economic development on environmental degradation can be obtained by differentiating the EKC baseline specification with respect to income per capita. Using the

baseline log transformed EKC model (4.2), the marginal effect of growth at any income level can be captured as:

$$\frac{\partial \ln(E)}{\partial \ln(y)} = \beta_1 + 2\beta_2\ (\ln(y) \qquad (3)$$

Model (4.3) shows that the effect of income on environmental degradation is not constant but depends on the level of income y. This implies that if $\beta_1 + 2\beta_2 \ln(y) > 0$, income increases environmental degradation; if $\beta_1 + 2\beta_2 \ln(y) < 0$, income reduces environmental degradation; and if $\beta_1 + 2\beta_2 \ln(y) = 0$, the economy is at the EKC turning point.

The income threshold or turning point occurs when the marginal effect of income from (3) equals zero:

$$\frac{\partial y}{\partial \ln(y)} = 0 \qquad \text{or} \qquad \beta_1 + 2\beta_2\ \ln(y) = 0$$

The income (y^*) turning point can therefore be calculated as:

$$\ln(y^*) = -\frac{\beta_1}{2\beta_2} \qquad \Rightarrow \qquad y^* = \exp(-\frac{\beta_1}{2\beta_2}) \qquad (4)$$

The turning point y^* represents the income level at which environmental degradation reaches the maximum before it starts to decline. A positive coefficient of β_1 and a negative coefficient of β_2 indicate an inverted U-shape relationship.

4. Results

4.1. Global EKC Evidence Using Fixed Effects Models

This section presents evidence of the EKC patterns at global level. It primarily employs fixed effects approaches to capture the structural relationship between income and environmental degradation and uses Lind Mehlum (2010) U-test to analyze whether the inverted U shape

relationship captured in the analysis is genuine and economically plausible. The section also analyzes residual variability to assess environmental heterogeneity beyond the estimated FE results.

Table 1 presents the FE baseline results with year fixed effects across multiple dimensions of environmental degradation, including emissions, particulate matter, depletion and forest damage.

Table 1. Baseline Fixed-Effects EKC Results (Global Sample)

Variable	(1) $lnCO_2pc$	(2) CO_2_I	(3) $lnCO_2$	(4) $lnCH_4$	(5) lnN_2O	(6) PM2.5	(7) NR Depl.	(8) Forest_D
lnGDPpc	**2.731*** **	0.268	**3.583*** **	**1.665*** **	**2.053*** **	**18.842*** **	−0.875	**−2.221*** **
	(0.496)	(0.324)	(0.602)	(0.328)	(0.458)	(5.583)	(0.698)	(0.699)
$lnGDPpc^2$	**−0.137*** **	**−0.053*** **	**−0.202*** **	**−0.094*** **	**−0.122** ***	**−1.191*** **	0.048	**0.120*** **
	(0.029)	(0.019)	(0.036)	(0.020)	(0.030)	(0.332)	(0.043)	(0.045)
Constant	**−12.434*** **	2.147	**−12.742*** **	**−4.656*** **	**−7.297** ***	**−41.592***	**5.343***	**0.681*** **
	(2.131)	(1.536)	(2.520)	(1.329)	(1.718)	(23.724)	(2.826)	(2.799)
Observations	3,725	3,725	3,725	3,725	3,725	3,725	3,619	3,623
Within R^2	0.39	0.26	0.54	0.38	0.36	0.12	0.14	0.19
Rho	0.96	0.96	0.99	0.99	0.99	0.94	0.92	0.92

*Note: Global N=149. Country & year FE; clustered SEs. GDP per capita and its square are the only independent variables. Year dummies included from 1996–2019 (1995 = base year). Constant reflects base-year intercept. NR Depl.: natural resource depletion (inverse hyperbolic sine); Forest D: forest damage/depletion (inverse hyperbolic sine). * p<0.10, ** p<0.05, *** p<0.01.*

Fixed effects results from table 1 show that the coefficients of both the linear and quadratic income terms display expected EKC signs for total GHG emissions, carbon emissions per capita and PM2.5. Carbon intensity does not show a significant EKC pattern because the linear term is not statistically significant while the quadratic term shows strong relationship with income. Forest damage exhibits a significant relationship with income, but that is not EKC as its coefficients exhibit reverse EKC directions, with negative coefficient for the linear income and positive

coefficient for the quadratic term. Natural resource depletion does not show a significant relationship with income. These results suggest that the EKC pattern is primarily a phenomenon that affects emissions and local pollutants but is limited to other environmental dimensions such as depletion.

The R-squared values reveal important variations in the dependent variables that are explained across environmental indicators. Total carbon emissions exhibit the highest variations explained in environmental outcomes (54%), followed by carbon emissions per capita (39%), methane (38 %) and nitrous oxide (36 %). PM2.5, forest damage and natural resource depletion display the lowest explanatory power.

To ensure that the models present a genuinely inverted income threshold that are not solely the results of the quadratic specification, the study employs the Lind-Mehlum (2010) U-test, reported in table 2 along with the income turning points at which environmental degradation peaks before it starts declining. The EKC income thresholds are only calculated for coefficients that satisfy the theoretical EKC conditions of a positive coefficient of GDP per capita and a negative one for GDP per capita squared.

Table 2. The Baseline EKC Income Turning Points

Indicator	β_1	β_2	ln(GDPpc*)	GDPpc* (USD)	Lind-Mehlum U-Test
CO_2 per capita	2.731***	−0.137***	9.97	$21,300	0.018 Valid
Total CO_2	3.583***	−0.202***	8.87	$7,100	0.000 Valid
CH_4	1.665***	−0.094***	8.86	$7,000	0.001 Valid
N_2O	2.053***	−0.122***	8.41	$4,500	0.001 Valid
PM2.5	18.842***	−1.191***	7.91	$2,700	0.004 Valid

Note: Turning point = $\exp(-\beta_1/2\beta_2)$. Lind-Mehlum (2010) U-test: Validated for all 5 indicators in the table. CO_2 Intensity, NR Depletion, Forest Damage excluded (no confirmed EKC).

The FE income turning points are about $21,300 for carbon emissions per capita, $7100 for total carbon emissions, $7000 for methane emissions, $4,500 for N2O and $2,700 for PM2.5.

The Lind-Mehlum test confirms the validity of these turning points as all five models reject the null hypothesis of the presence of a monotonic relationship. However, the income threshold for carbon emissions per capita appears within reach for most high-income countries but beyond the income range of developing countries.

The income threshold for the total emissions appears relatively lower than the global average but still higher than the average income in developing countries. PM2.5 income threshold emerges as the most achievable income turning point for both high income and low-income economies as it occurs at lower income levels, suggesting that improvements in local air quality do not necessarily require higher income.

Regional and Climatic Heterogeneity in Environmental Outcomes

To assess environmental heterogeneity beyond the estimated baseline EKC, I computed the standard deviation of the residuals for each country and then average within each continent and climate zone. These residuals measure unexplained variations, dispersion around the fitted values and instability in environmental outcomes after accounting for both the linear and quadratic income and year fixed effects.

Table 3. Average Standard Deviation of the Residuals by Continent (Emissions)

(A) Mean Standard Deviation of the Residuals by Continent (Emissions)						
Continent	**CO2_pc**	**CO2 total**	**CH4 total**	**N2O total**	**PM2.5**	**N**
Africa	0.2195	0.2308	0.1444	0.1174	3.1173	47
Americas	0.1135	0.1322	0.082	0.0905	3.4574	25
Asia	0.1781	0.2034	0.1356	0.1577	3.9782	37
Europe	0.1642	0.225	0.1234	0.1236	1.8664	37
Oceania	0.0911	0.1091	0.1093	0.1326	1.9597	3
Total	0.1533	0.1801	0.1189	0.1244	2.8758	149
(B) Mean Standard Deviation of the Residuals by Climate Zone (Emissions)						
Climate Zone	**CO2_pc**	**CO2 total**	**CH4 total**	**N2O total**	**PM2.5**	**N**
Arid	0.1624	0.1941	0.1258	0.1376	4.8288	23
Continental	0.1592	0.2236	0.1333	0.111	2.4525	26
Mediterranean	0.087	0.1106	0.164	0.1052	2.6365	1
Temperate	0.1574	0.183	0.0954	0.1085	2.0478	37
Tropical	0.1984	0.2125	0.1403	0.1358	3.2555	62
Total	0.1529	0.1848	0.1317	0.1196	3.0442	149

The results reveal important differences in environmental variability across climate zones and continents. Across continents, PM2.5 displays the highest residual variability, particularly Asia (3.98), followed by America (3.46) and Africa (3.12). These high dispersion levels in PM2.5 outcomes indicate that particulate matter is considerably more heterogeneous across countries, particularly in the developing world and remains influenced by additional factors that are not directly captured by income. Among greenhouse gas emissions, Africa exhibits the highest residual variability for carbon emissions per capita (0.220), while Europe and Asia show relatively high variability for total carbon emissions and nitrous oxide emissions. These results reflect differences in industry structures, energy sources and other unexplained factors that predict these global emissions.

On the other hand, America and Oceania display the lowest residual variability for greenhouse gases. The climate zone analysis of environmental variability also reveals a similar pattern.

Tropical countries exhibit the highest dispersion for carbon emissions per capita (0.198) and very high variability in total carbon (0.213), methane (0.140), and nitrous oxide (0.136). These results likely reflect differences in land-use practices, energy systems, and agriculture production that often influence these outcomes beyond income. On the other hand, arid zones display high variations for PM2.5 (4.829), followed by tropical zones (3.256) while continental and temperate countries show relatively high variations for total carbon emissions.

Overall, the findings demonstrate that environmental outcomes remain heterogeneous across geographic conditions, including continents and climate characteristics. They motivate the study objective to evaluate contextual factors that are not directly captured in the baseline models.

4.2. Global EKC Evidence Using Dynamic Panels: System GMM and PMG

To ensure robustness of the findings, the study presents the global EKC results using dynamic panels, including System GMM and PMG.

A. Robustness Using the two-step System GMM

The two-step System GMM approach is employed to capture environmental persistence and potential endogeneity (Blundell & Bond, 1998). This approach is particularly important because various dimensions of environmental degradation, including emissions, local pollution and resource depletion evolve slowly and gradually over time and do not necessarily adjust immediately to income growth.

Table 4. Baseline EKC Models (Global Sample, GDP Terms Only, System GMM)

Variable	(1) $lnCO_2pc$	(2) CO_2_I	(3) $lnCO_2$	(4) $lnCH_4$	(5) lnN_2O	(6) NR Depl.	(7) Forest_D
L.Dependent	1.020***	0.912***	1.001***	0.973***	0.981***	0.693***	0.991***
	(0.030)	(0.031)	(0.023)	(0.017)	(0.014)	(0.060)	(0.035)
lnGDPpc	0.237	0.054	0.316**	0.244***	0.233***	−0.932***	0.020
	(0.162)	(0.082)	(0.145)	(0.075)	(0.065)	(0.343)	(0.139)
$lnGDPpc^2$	−0.016*	−0.003	−0.020**	−0.015***	−0.014***	0.044**	−0.001
	(0.008)	(0.005)	(0.008)	(0.004)	(0.004)	(0.019)	(0.007)
Observations	3,576	3,576	3,576	3,576	3,576	3,469	3,474
Countries	149	149	149	149	149	148	148
Instruments	10	10	10	10	10	10	10
AR(1) p	0.000	0.000	0.000	0.000	0.001	0.000	0.000
AR(2) p	0.244	0.891	0.243	0.379	0.637	0.000	0.593
Hansen p	0.083	0.051	0.032	0.041	0.016	0.001	0.075

*Note: Two-step System GMM; Windmeijer-corrected SEs. GMM instruments: L(2/3) of dependent. GDP terms treated as IV-style instruments. NR Depl: natural resource depletion (inverse hyperbolic sine); Forest D: forest damage/depletion (inverse hyperbolic sine). * p<0.10, ** p<0.05, *** p<0.01.*

The system GMM EKC estimates at global level show strong persistence in environmental outcomes and highlight important change in the EKC relationship for certain indicators compared to the fixed-effect approach. The estimated lagged dependent variables are highly significant and positive across all environmental indicators, with coefficients ranging from 0.693*** for natural resource depletion to 1.020*** for carbon emissions per capita, revealing strong path dependence of emissions levels. However, the near-unit-root persistence over-absorbs the cross-sectional variations, which masks the structural relationship between income and environmental outcomes.

The dynamic approach broadly supports the baseline EKC relationship for total carbon emissions, methane emissions and nitrous oxide emissions. Compared to the fixed effects, the income coefficients for these indicators display smaller magnitude, particularly since part of the variations is captured by the lagged dependent variables, reflecting environmental persistence over time. However, the diagnostic tests across most GMM models suggest that these results should be

interpreted with caution. Year dummies are excluded from the baseline System GMM estimation to further limit instrument proliferation, which can introduce severe econometric problems (Tamazian & Rao, 2010; Shahbaz & Shabbir, 2012; Baek, 2015). All specifications satisfy the expected AR(1) conditions while AR(2) test for second order serial correlation is passed by all models with the exception of PM2.5 (model 5) and natural resource depletion (model 7).

Several specifications fail the Hansen test, particularly models 3, 4, 5, and 6, raising serious concerns about instrument validity (Hansen test p-value > 0.05). The Hansen test for models 2 remains at borderline while models 1 and 7 weakly pass the Hansen test (*). This weaker diagnostic performance limits the reliability of the System GMM estimates as the primary basis for inference.

Overall, the comparison between the baseline fixed effects (table 5.8) and the system GMM estimates reveals meaningful divergences for four of the eight indicators: carbon emissions per capita, PM2.5, natural resource depletion, and forest damage. These divergences carry important methodological implications. First, for carbon emissions per capita and forest depletion, the near unity lagged coefficients absorb most of the income variation, which considerably weakens the estimated EKC relationship. For PM2.5 and natural resource depletion, the Hansen and AR (2) tests fail, questioning the reliability of the coefficients of these two environmental indicators.

These divergences underscore the importance of dynamic adjustment and pollutant-specific environmental processes while highlighting that FE estimations are often upward biased due to dynamic misspecifications. However, the principal conclusions regarding the GHG emissions remain qualitatively unchanged.

B. Robustness Using Pool Mean Group Regression

The pooled mean group (PMG) approach is employed to further investigate the long-run relationship between CO2 emissions and GDP per capita while accounting for non-stationarity and cointegration (Pesaran et al., 1999). This estimation technique is well suited for analyzing the

growth-environment relationship and it allows the study to capture heterogeneous short-run dynamics and common long-run equilibrium relationships across countries. The PMG approach is based on autoregressive distributed lag (ARDL) error correction framework and is appropriate for variables with unit roots but remain cointegrated over time (Pesaran & Smith, 1995; Blackburne & Frank, 2007; Asongu et al., 2020).

Table 5. Pooled Mean Group (PMG) Baseline EKC Models (Global Sample)

Variable	(1) $lnCO_2pc$	(2) CO_2_I	(3) $lnCO_2$	(4) $lnCH_4$	(5) lnN_2O	(6) PM2.5	(7) NR Depl.
LONG-RUN (ec)							
lnGDPpc	5.013***	0.562***	6.644***	1.458***	1.129***	7.784**	−0.066
	(0.240)	(0.071)	(0.274)	(0.126)	(0.117)	(3.739)	(0.049)
$lnGDPpc^2$	−0.275***	−0.038***	−0.344***	−0.074***	−0.049***	−0.914***	0.004
	(0.014)	(0.004)	(0.016)	(0.008)	(0.007)	(0.227)	(0.003)
SHORT-RUN (SR)							
Error Correction (ec)	−0.209***	−0.207***	−0.181***	−0.161***	−0.302***	−0.261***	−0.341***
	(0.015)	(0.015)	(0.015)	(0.015)	(0.023)	(0.022)	(0.016)
ΔlnGDPpc	−3.308	0.644	−2.937	1.182	0.552	282.020	−21.419
$\Delta lnGDPpc^2$	0.144	−0.067	0.119	−0.042	0.002	−17.030	1.321
Observations	3,576	3,576	3,576	3,576	3,576	3,576	3,469

*Note: PMG estimator (Pesaran et al., 1999). All EC terms are negative and significant (validates cointegration). Short-run income effects are uniformly insignificant. NR Depl: natural resource depletion (inverse hyperbolic sine). * p<0.10, ** p<0.05, *** p<0.01.*

The PMG results depicted in table 5 provide strong evidence of the long-run relationship between economic development and environmental degradation but show no significant short-run income effects. For all indicators except for natural resource depletion, the linear GDP per capita term displays positive coefficient while the quadratic GDP per capita term exhibits a negative coefficient, both significant at all levels. The EKC hypothesis is therefore observed for carbon emissions per capita, carbon intensity, total carbon emissions, methane emissions, nitrous emissions, and PM2.5 exposure. These results reinforce the robustness of the baseline fixed effects

EKC findings for pollution and continue to show that the EKC relationship does not exist for depletion-based degradation.

However, the income turning points from the Pool Mean Group (PMG) estimated for carbon emissions per capita, total carbon emissions and methane emissions are approximately $9,000, $15,000, and $19,000, respectively. These values can be observed across upper middle income and high-income economies. However, the turning point for nitrous oxide emissions is estimated at $100,900, which appears substantially above the income range of most countries in the sample while the estimated turning point for $PM_{2.5}$ of $71 lies far below the income distribution and therefore lacks substantive meaning as it appears implausible and out of sample. Therefore, these turning points are less economically meaningful and should be interpreted cautiously as they appear to be an artifact of the EKC functional form.

The estimated error-correction terms are negative and significant across all specified models, which validates the use of PMG, confirming cointegration and stable long-run equilibrium relationship between income per capita and air pollutants. The adjustment speed appears moderate and varies across environmental indicators. Nitrous oxide and PM 2.5 exhibiting faster convergence dynamics as they display the adjustment speed of about 30 % and 26.1 % per year, respectively, compared to carbon per capita (21%), carbon intensity (21%), total carbon emissions (18%) and methane (16 %). All short run income coefficients are not statistically significant across all models, revealing strong absence of their short-run effects on environmental outcomes.

These findings are central to this study. They suggest that environmental outcomes do not respond immediately to annual income fluctuations. Rather, they demonstrate that environmental outcomes are primarily driven by long-run effects of income such as structural transformation, industrialization, technological change, energy use, and other contextual factors that this

dissertation attempts to capture. In this context, EKC should be apprehended as a long-run adjustment process rather than short run response to income change.

To capture more differences across countries, table 3 summarizes the main characteristics of environmental and income indicators in developing countries (G-77 sample) and developed countries (OECD).

4.3.EKC FE Results Across Development Groups: G-77 vs OECD

The FE EKC estimations using OECD and G77 samples highlight important differences across the development groups at global levels, particularly EKC patterns. The G77 EKC results strongly confirm the EKC patterns for carbon emissions per capita, total carbon, and PM2.5 but also reveals weakened EKC patterns for methane and nitrous oxide emissions. However, the FE results using the OECD sample show no significant EKC-type relationships between income and environmental pressure. These results suggest that the EKC relationship remains a developing country 'phenomenon as income alone does not strongly predict either exacerbation or improvements in environmental conditions in rich OECD countries.

Table 6. Baseline EKC Results (G-77 Sample)

Variable	(1) $lnCO_2pc$	(2) CO_2_I	(3) $lnCO_2$	(4) $lnCH_4$	(5) lnN_2O	(6) PM2.5	(7) NR Depl.	(8) Forest_D
lnGDPpc	1.835***	0.470	2.150***	0.814**	1.579*	16.734**	−1.254	−2.283**
	(0.549)	(0.312)	(0.644)	(0.370)	(0.803)	(8.066)	(0.894)	(0.981)
$lnGDPpc^2$	−0.082**	−0.063***	−0.112***	−0.040*	−0.099*	−1.119**	0.072	0.121*
	(0.034)	(0.024)	(0.039)	(0.024)	(0.053)	(0.515)	(0.056)	(0.067)
Observations	2,475	2,475	2,475	2,475	2,475	2,475	2,419	2,423
Within R^2	0.47	0.28	0.68	0.51	0.47	0.10	0.13	0.21
Rho	0.96	0.97	0.98	0.99	0.99	0.94	0.90	0.91

*Note: Country and year FE; clustered SEs. G-77 sample. NR Depl: natural resource depletion (inverse hyperbolic sine); Forest D: forest damage/depletion (inverse hyperbolic sine). * p<0.10, ** p<0.05, *** p<0.01.*

Table 7. Baseline EKC Models (OECD Sample, GDP Terms Only, FE)

	(1) lnCO₂pc	(2) CO₂_I	(3) lnCO₂	(4) lnCH₄	(5) lnN₂O	(6) PM2.5	(7) NR Depl.	(8) Forest D.
lnGDPpc	2.349** (1.122)	−1.848* (0.936)	1.205 (1.589)	0.610 (1.209)	1.258 (0.792)	−29.174 (19.052)	−0.724 (1.934)	−1.320 (1.270)
lnGDPpc_sq	−0.094 (0.059)	0.074 (0.046)	−0.039 (0.081)	−0.026 (0.060)	−0.036 (0.045)	1.753* (1.024)	0.026 (0.095)	0.059 (0.059)
Constant	−11.926** (5.371)	11.491** (4.837)	−3.442 (7.861)	−0.399 (6.058)	−6.660* (3.513)	135.221 (89.154)	5.023 (9.904)	7.272 (6.771)
Observations	900	900	900	900	900	900	883	883
Within R^2	0.485	0.647	0.225	0.091	0.374	0.715	0.217	0.182
Rho	0.954	0.931	0.994	0.996	0.996	0.979	0.903	0.749

*Notes: Baseline EKC specification, GDP terms only, OECD sample. Country and year fixed effects included; standard errors clustered by country in parentheses. CO₂_I: carbon intensity; NR Dep: natural resource depletion (inverse hyperbolic sine); Forest D: forest damage/depletion (inverse hyperbolic sine). * p<0.10, ** p<0.05, *** p<0.01.*

The income turning points of the G77 baseline EKC and the Lind-Mehlum U-test are presented in table 7. The U-test results strongly confirm the EKC turning points for PM2.5 and weakly for total carbon emissions and nitrous oxide emissions. The PM2.5 income threshold for the G77 sample is estimated at $1,770, which appears relatively lower than the global sample income threshold. Similarly, nitrous oxide emissions also exhibit relatively lower income threshold ($2,900) compared to the global sample ($4,500) but its Lind-Mehlum validation remains on the borderline.

Table 8. The EKC Turning Point in the Baseline Model (G77) with U-Test

Indicator	β1	β2	ln(GDPpc*)	GDPpc*	U-Test
CO_2 per capita	1.835***	-0.082**	11.19	$72,300	0.397
CO_2	2.150***	-0.112***	9.60	$14,800	0.064
CH_4	0.814**	-0.040*	10.18	$26,300	0.272
N_2O	1.579*	-0.099*	7.97	$2,900	0.052
PM2.5	16.734**	-1.119**	7.48	$1,770	0.047

Total carbon emissions and methane display substantially higher turning points, completely out of reach for developing countries and not validated by the U-test. The per capita carbon emissions turning point of $72,300 exceeds the GDP per capita of every G-77 country in the sample and the Lind-Mehlum test (p=0.397) confirms this does not constitute a valid EKC relationship within the observable income range. Similarly, methane's turning point of $26,300 is not validated by the U-test and appears far greater than the income levels of most developing countries. Compared to the global income turning points, the G77 sample exhibits very high-income turning points for GHG emissions, with carbon emissions per capita showing a very large income threshold.

5. Discussion

5.1. The Environmental Kuznets Curve is Conditional Rather than Universal

One of the central findings of this paper is that the EKC hypothesis should be interpreted as a conditional rather than universal relationship. Across all specifications, evidence supporting the conventional inverted-U income-environment relationship varies considerably across environmental indicators and income group. Results reveal that the EKC hold globally for most pollutants, remain stronger for developing countries but does not hold in OECD countries. Across all empirical specifications, the hypothesis receives its strongest and most consistent support for particulate matter (PM2.5) exposure, whose estimated income (GDP per capita) turning points are estimated at approximately US $1,770 for Global South and US $2,700 globally. These turning points are statistically validated by the Lind-Mehlum (2010) test and fall within income levels that are attainable for many developing countries. This finding supports earlier work by Grossman and

Krueger (1991) and Shafik (1994), who argued that local pollutants tend to improve at relatively early stages of economic development.

The evidence for greenhouse gas emissions is considerably more nuanced. Although carbon emissions per capita and total carbon emissions consistently display the expected positive income and negative quadratic income relationship, the estimated turning points lie far beyond the income range observed for most developing countries and fail the Lind-Mehlum test. This indicates that economic growth alone is unlikely to generate meaningful reductions in carbon emissions within the foreseeable development trajectory of most developing countries. The reliability of the EKC income turning point therefore carries important theoretical implications. Many studies probably interpret statistically significant linear and quadratic income terms as sufficient evidence of an Environmental Kuznets Curve but fail to validate whether the turning point is genuine or remains the artifact of the quadratic specification (Bettarelli et al., 2026).

Unlike Bettarelli et al. (2026), who identify a global EKC turning point ($25,000) for carbon emissions that is confirmed across various regions, this study demonstrates that these interpretations may overstate empirical support for the hypothesis. The invalid carbon emissions turning point in this study reinforces Riti et al. (2017)' s EKC analysis in China, which found the carbon emissions turning point to be economically implausible. They reinforce the conclusion that income-driven environmental improvements are unlikely to generate meaningful reductions in carbon emissions economies for developing economies. These findings align with Burke et al. (2015) who have also found that income elasticities of carbon emissions remain positive across the development trajectory in developing countries.

A likely explanation is that PM2.5 is a local pollutant whose costs are immediately visible to households and policymakers, creating incentives for regulation at relatively low-income levels.

Additionally, as income grows at the initial development level, countries adopt cleaner technologies, reinforce environmental regulation, and respond to rising public demand for improved local environmental quality. However, greenhouse gas emissions generate global externalities whose benefits from abatement are more diffuse, reducing incentives for emission reductions through income growth alone.

For natural resource depletion and forest damage, the study did not find evidence of an EKC relationship. Natural resource depletion and forest degradation differ even more fundamentally from pollution indicators. Unlike atmospheric pollutants, these measures reflect changes in natural capital rather than emissions intensity. The absence of an EKC relationship for these indicators should not be interpreted as evidence against sustainable development but rather as confirmation that different forms of environmental degradation operate through distinct mechanisms.

The comparison of the EKC results between OECD and G77 samples highlights important structural differences between developing and high-income countries that require further attention. They show that environmental outcomes cannot be solely captured through income alone but also by a combination of various contextual factors. In OECD for instance, the absence of significant EKC relationships may be explained by the fact that most OECD countries may have income levels already higher than EKC turning points in addition to potential reduced income variation and structural convergence. OECD countries often establish strong environmental regulations, and most countries prefer outsourcing polluting activities abroad to avoid penalties. Furthermore, the analysis of the baseline FE residual volatility by continent and climate type reinforces regional differences regarding EKC patterns.

Overall, these results challenge the interpretation of the EKC as a universal solution for environmental improvement. Instead, the study indicates that the relationship between economic development and environmental quality is conditional and pollutant specific, whose validity depends on the type of environmental degradation examined, the income range under consideration, and other structural context in which development occurs.

The findings directly address the robustness and generalization concerns raised by Stern (2004), who demonstrated that the apparent universality of the EKC often reflects model specification choices rather than a genuine environmental law, and supported by Carson (2010), highlighting that the income-environment relationship differs substantially across pollutants, countries, and institutional contexts.

The study, therefore, underscores the necessity to distinguish pollution-based degradation and depletion-based degradation, which some EKC studies tend to mix. Consequently, policies based solely on the expectation that environmental quality will improve automatically as income rises are unlikely to produce sustainable environmental outcomes in developing countries.

5.2. The EKC as a Long-run Equilibrium Relationship

The use of fixed effects (FE), complemented by System GMM and Pool Mean Group (PMG) estimators for robustness demonstrates that the income-environment relationship is fundamentally a long-run structural process rather than a short-run macroeconomic response. Each estimator captures a distinct dimension of environmental change, and their joint interpretation yields insights that would be unavailable from any single approach.

The fixed-effects models identify the structural relationship between income and environmental degradation after controlling for unobserved, time invariant country-specific characteristics. This makes them particularly well suited for examining regional heterogeneity and

long-run differences across countries that the EKC overlooks. The FE results show that the EKC is highly sensitive to unobserved factors that vary systematically across regions or income groups, suggesting that relying only on significant income effects may mislead the true EKC behavior.

The System GMM models reveal substantial persistence in environmental outcomes, indicating that these outcomes are heavily influenced by their historical levels that shape current environmental conditions. This finding suggests that environmental degradation evolves gradually through cumulative processes, where past emissions strongly influence current outcomes and income explains only a portion of subsequent environmental change, consistent with findings reported by Guliyev & Seyfullayev (2025). The PMG estimates provide further evidence that the Environmental Kuznets Curve is primarily a long-run equilibrium relationship.

This study underscores the importance of recognizing the path-dependent nature of environmental degradation and its long run structural relationship with economic development. The results show that static and dynamic approaches are not substitutes but complementary tools. Each approach captures a different dimension of the growth-environment relationship, particularly given the non-stationarity of environmental indicators and the persistence in environmental conditions. A key methodological concern raised by Tamazian & Rao (2010) is that static models often overstate the income-environment relationship. This is reflected particularly in the high magnitude and strong significance of coefficients displayed in the FE models, which suggest an EKC pattern even when environmental outcomes are strongly influenced by slow-moving, cumulative processes. The dynamic System GMM reinforces this point by revealing high persistence in environmental indicators, implying that environmental conditions adjust gradually and self-reinforce unless strong intervention occurs.

From a policy standpoint, capturing persistence reinforces the need for effective and permanent policy with strong commitments. However, persistence alone does not fully illuminate the true mechanisms through which environmental strategies and policy design can be shaped, especially when much of the variations in environmental outcomes are attributed to their historical levels. Capturing structural differences remains therefore essential for achieving environmental policy outcomes, including long run policy processes that shape structural transformation. These findings suggest that environmental improvements emerge primarily through long run income effects, such as gradual structural adjustments, including technological progress, changes in energy systems, rather than through temporary fluctuations in economic growth.

This conclusion contrasts with studies such as Demissew Beyene & Kotosz (2020), who report EKC dynamics as a short-run relationship for countries. By employing a broader range of environmental indicators, a longer period of analysis, and multiple complementary estimation techniques, this study demonstrates that the income-centered EKC relationship is better understood as a long-term process of structural transformation than as an immediate response to business cycle movements. Temporary periods of economic growth or recession are unlikely to alter environmental trajectories unless accompanied by sustained changes in the underlying economic and institutional structure. The income-environment relationship adjusts over decades, not years, reinforcing the importance of long-term, credible policy commitments rather than environmental strategies tied to short-run macroeconomic conditions.

6. Conclusion

The study examines the baseline, income-centered Environmental Kuznets curve (EKC) relationship between environmental degradation and economic development across multiple environmental indicators. Unlike much of the existing literature, which focuses primarily on

carbon emissions, this study incorporates both pollution-based indicators (carbon emissions, methane emissions, nitrous oxide emissions, and particulate matter 2.5) and resourced-based indicators (natural resource depletion and forest damage). The study suggests that EKC validity depends on the environmental indicator used and that conclusions derived from emissions-based measures cannot be generalized to environmental degradation as a whole. Pollution-based and resource-based environmental indicators follow systematically different EKC patterns.

The results demonstrate that the EKC is predominantly a phenomenon associated with pollution-based degradation. The analysis supports the presence of a non-linear and inverted relationship between income and several indicators of pollution, particularly carbon emissions, methane emissions, nitrous emissions and PM2.5 exposure, with validated income turning points, only globally. Resource-based degradation does not exhibit EKC patterns and, in many occasions, shows limited relationship with income, suggesting that income growth does not automatically worsen or improve natural resource conservation or forest damage. Specifically, forest damage exhibits reverse EKC pattern, while natural resource depletion displays no significant relationship with income.

The study also reveals important EKC differences across regions and demonstrates that significant EKC patterns do not necessarily imply valid income thresholds. Estimations of the EKC across subsamples have demonstrated that the EKC is observed globally and partially in developing countries (G77 sample) but remains absent in high income countries (OECD sample). The analysis shows that while the EKC patterns can be captured in developing countries, the estimated turning points lie far beyond developing countries' income range, questioning the true existence of an inverted U-shape relationship in the region. Among all environmental indicators,

particulate matter (PM2.5) consistently exhibits the most achievable turning points for developing countries with income turning points occurring at lower income levels.

Furthermore, the panel dynamic estimators reveal that the EKC relationship is a long run adjustment process influenced by country's specific contexts and environmental persistence. Income growth only explains certain aspects of environmental outcomes but remains limited to explaining the mechanisms driving environmental improvements, particularly in developing countries. The considerable variations in environmental indicators, regions, and estimation techniques demonstrate that environmental outcomes are shaped not only by income, but also by broader structural and geographic conditions that are not necessarily associated with income. These findings suggest that the EKC is not universal but depends on both the regional contexts and the dimension of environmental degradation being evaluated.

Despite providing important insights, the income-centered EKC analysis presented in this study has several limitations. First, the parsimonious income-centered specification may be subject to omitted-variable bias because environmental outcomes are also influenced by institutional quality, economic structure, geographic characteristics, technological change, energy composition, and urbanization. Second, despite employing dynamic panel estimators and cointegration techniques, the analysis remains observational and should not be interpreted as establishing causal effects. Finally, national-level indicators may mask important within-country environmental heterogeneity. These limitations require the inclusion of additional factors that could also significantly affect environmental performance. Therefore, moving beyond income-based EKC models to capture the geographic, structural and institutional dimensions remain critical in the exploration of the growth-environment dynamics.

References

Asongu, S. A., Agboola, M. O., Alola, A. A., & Bekun, F. V. (2020). The criticality of growth, urbanization, electricity and fossil fuel consumption to environmental sustainability in Africa. Science of the Total Environment, 712, 136376.

Baek, J. (2015). Environmental Kuznets curve for CO_2 emissions: The case of Arctic countries. Energy Economics, 50, 13–17.

Baltagi, B. H. (2008). Econometric analysis of panel data (4th ed.). John Wiley & Sons.

Bettarelli, L., Furceri, D., Loungani, P., Ostry, J. D., & Pisano, L. (2026). Environmental Kuznets curve and green regulation. *Structural Change and Economic Dynamics*.

Blackburne III, E. F., & Frank, M. W. (2007). Estimation of nonstationary heterogeneous panels. The Stata Journal, 7(2), 197–208.

Blundell, R., & Bond, S. (1998). Initial conditions and moment restrictions in dynamic panel data models. Journal of Econometrics, 87(1), 115–143.

Bond, S., Hoeffler, A., & Temple, J. (2001). GMM Estimation of Empirical Growth Models.

Burke, P. J., Shahiduzzaman, M., & Stern, D. I. (2015). Carbon dioxide emissions in the short run: The rate and sources of economic growth matter. *Global Environmental Change*, *33*, 109-121.

Carson, R. T. (2010). The environmental Kuznets curve: seeking empirical regularity and theoretical structure. *Review of environmental Economics and Policy*. https://doi.org/10.1093/reep/rep021.

Chu, L. K. (2021). Economic structure and environmental Kuznets curve hypothesis: New evidence from economic complexity. Applied Economics Letters, 28(7), 612–616.

Clapp, J., & Dauvergne, P. (2011). Paths to a green world: The political economy of the global environment. MIT Press.

Dasgupta, S., Laplante, B., Wang, H., & Wheeler, D. (2002). Confronting the environmental Kuznets curve. Journal of Economic Perspectives, 16(1), 147–168.

Demissew Beyene, S., & Kotosz, B. (2020). Testing the environmental Kuznets curve hypothesis: an empirical study for East African countries. *International Journal of Environmental Studies*, *77*(4), 636-654.

Dinda, S. (2004). Environmental Kuznets curve hypothesis: A survey. Ecological Economics, 49(4), 431–455.

Feenstra, R. C., Inklaar, R., & Timmer, M. P. (2025). *Penn World Table version 11.0* [Data set]. Groningen Growth and Development Centre. https://doi.org/10.34894/FABVLR.

Grossman, G. M., & Krueger, A. B. (1991). Environmental impacts of a North American free trade agreement (NBER Working Paper No. 3914). National Bureau of Economic Research. https://www.nber.org/papers/w3914

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. The Quarterly Journal of Economics, 110(2), 353–377.

Guliyev, H., & Seyfullayev, I. (2025). Is the environmental Kuznets curve hypothesis valid for all countries? Fresh insights from bias-corrected dynamic panel data models. *Journal of Environmental Management*, *393*, 126960.

Hausman, J. A. (1978). Specification tests in econometrics. Econometrica, 46(6), 1251–1271.

Hettige, H., Mani, M., & Wheeler, D. (2019). Industrial pollution in economic development: The environmental Kuznets curve revisited. In The economics of water quality (pp. 27–58). Routledge.

Kuznets, S. (2019). Economic growth and income inequality. In The gap between rich and poor (pp. 25–37). Routledge. (Original work published 1955)

Levin, A., Lin, C. F., & Chu, C. S. J. (2002). Unit root tests in panel data: Asymptotic and finite-sample properties. Journal of Econometrics, 108(1), 1–24.

Lind, J. T., & Mehlum, H. (2010). With or without U? The appropriate test for a U-shaped relationship. Oxford Bulletin of Economics and Statistics, 72(1), 109–118.

Mills, J. H., & Waite, T. A. (2009). Economic prosperity, biodiversity conservation, and the environmental Kuznets curve. Ecological Economics, 68(7), 2087–2095. https://doi.org/10.1016/j.ecolecon.2009.01.017

Panayotou, T. (1993). Empirical tests and policy analysis of environmental degradation at different stages of economic development (Working Paper WP238). Technology and Employment Programme, International Labour Office.

Panayotou, T. (1997). Demystifying the environmental Kuznets curve: Turning a black box into a policy tool. Environment and Development Economics, 2(4), 465–484.

Pesaran, M. H. (2021). General diagnostic tests for cross-sectional dependence in panels. Empirical Economics, 60(1), 13–50. https://doi.org/10.1007/s00181-020-01875-7

Pesaran, M. H., & Smith, R. (1995). Estimating long-run relationships from dynamic heterogeneous panels. Journal of Econometrics, 68(1), 79–113.

Pesaran, M. H., Shin, Y., & Smith, R. P. (1999). Pooled mean group estimation of dynamic heterogeneous panels. Journal of the American Statistical Association, 94(446), 621–634.

Polat, B., & Çil, N. (2025). Investigating the environmental Kuznets curve modified with HDI: Evidence from a panel of eco-innovative countries. Environment, Development and Sustainability, 27(7), 16655–16682.

Riti, J. S., Song, D., Shu, Y., & Kamah, M. (2017). Decoupling CO2 emission and economic growth in China: is there consistency in estimation results in analyzing environmental Kuznets curve?. *Journal of cleaner production*, *166*, 1448-1461. https://doi.org/10.1016/j.jclepro.2017.08.117

Sanford, J. E. (2003). Developing countries: Definitions, concepts and comparisons. Nova Publishers.

Selden, T. M., & Song, D. (1994). Environmental quality and development: Is there a Kuznets curve for air pollution emissions? Journal of Environmental Economics and Management, 27(2), 147–162. https://doi.org/10.1006/jeem.1994.1031

Shafik, N. (1994). Economic development and environmental quality: An econometric analysis. Oxford Economic Papers, 46(Suppl. 1), 757–773. https://doi.org/10.1093/oep/46.Supplement_1.757

Shafik, N., & Bandyopadhyay, S. (1992). Economic growth and environmental quality: Time-series and cross-country evidence (Vol. 904). World Bank Publications.

Shahbaz, M., Lean, H. H., & Shabbir, M. S. (2012). Environmental Kuznets curve hypothesis in Pakistan: Cointegration and Granger causality. Renewable and Sustainable Energy Reviews, 16(5), 2947–2953. https://doi.org/10.1016/j.rser.2012.02.015

Ssekibaala, D. S., Ariffin, M. I., & Duasa, J. (2022). Economic growth, international trade, and environmental degradation in Sub-Saharan Africa. Journal of Economics and Development, 24(4), 293–308.

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. World Development, 32(8), 1419–1439.

Stern, D. I., Common, M. S., & Barbier, E. B. (1996). Economic growth and environmental degradation: The environmental Kuznets curve and sustainable development. World Development, 24(7), 1151–1160. https://doi.org/10.1016/0305-750X(96)00032-0

Tamazian, A., Chousa, J. P., & Vadlamannati, K. C. (2009). Does higher economic and financial development lead to environmental degradation? Evidence from BRIC countries. Energy Policy, 37(1), 246–253. https://doi.org/10.1016/j.enpol.2008.08.025

Tamazian, A., & Rao, B. B. (2010). Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. Energy Economics, 32(1), 137–145.

Wang, H., & Wheeler, D. (2003). Equilibrium pollution and economic development in China. Environment and Development Economics, 8(3), 451–466. https://doi.org/10.1017/S1355770X030024X

Wooldridge, J. M. (2010). Econometric analysis of cross section and panel data. MIT Press.

World Health Organization. (2021). WHO global air quality guidelines: Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. https://www.who.int/publications/i/item/9789240034228

Xaisongkham, S., & Liu, X. (2024). Institutional quality, employment, FDI and environmental degradation in developing countries: evidence from the balanced panel GMM estimator. *International Journal of Emerging Markets*, *19*(7), 1920-1939.

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DECLARATIONS

Ethics declaration

Ethics declaration: Not applicable.

This study analyzes publicly available aggregate country-level secondary data. It does not involve human participants, identifiable personal information, animal research, or biological materials.

Clinical trial number

Clinical trial number: not applicable.

Consent to Publish declaration

Consent to Publish declaration: not applicable.

Consent to Participate declaration

Consent to Participate declaration: not applicable.

Data Availability Statement

The sources of data analyzed in this study are publicly available from the World Bank's World Development Indicators and the Penn World Table, version 11.0:

World Development Indicators: World Bank. (2025a). *World development indicators 2025*. The World Bank Group. https://databank.worldbank.org/source/world-development-indicators

Penn World Table, version 11.0: Feenstra, R. C., Inklaar, R., & Timmer, M. P. (2025). *Penn World Table version 11.0* [Data set]. Groningen Growth and Development Centre.

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The assembled analysis dataset, including the variable definitions and transformations used in this study, is available from the corresponding author upon reasonable request, subject to the source providers' applicable terms of use.

Code availability

The author ensures that all data, materials, software applications and custom code support their published claims and comply with field standards.

The data-cleaning, variable-construction, and statistical-analysis scripts used to produce the reported results are available from the corresponding author upon reasonable request.

Author contributions

Fustel Mwamba Ngalula was responsible for conceptualization, research design, data collection and curation, methodology, statistical analysis, interpretation of results, visualization, and manuscript preparation and revision. The author approved the submitted manuscript and takes responsibility for its content.

Use of generative artificial intelligence

Generative artificial intelligence tools were used to assist with document formatting, preparation of tables, and language proofreading. The author reviewed and verified the resulting content and takes full responsibility for the accuracy, originality, and integrity of the manuscript.

All substantive scholarly contributions, including conceptual development, literature review, research design, econometric model specification, statistical analysis, interpretation of findings, discussion, and conclusions, were independently undertaken by the author.

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