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Does Growth Clean Up After Itself? A Multi-Gas Test of the Environmental Kuznets Curve

Snober Fazal[1], Javaiz Alam[2], Faiza Mudassir[3]

[1] Assistant Professor, Department of Agriculture and Resource Economics, MNS University of Agriculture Multan, Pakistan. Email: snober.fazal@mnsuam.edu.pk
[2] Assistant Professor, Department of Agronomy, MNS University of Agriculture Multan, Pakistan. Email: javiz.alam@mnsuam.edu.pk
[3] Assistant Professor, Faculty of Social Sciences and Humanities, MNS University of Agriculture Multan, Pakistan. Email: faiza.mudassir@mnsuam.edu.pk

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ABSTRACT

This study reexamines the Environmental Kuznets Curve (EKC) hypothesis in developing economies, identifying which greenhouse gas CO_2, CH_4, or N_2O most influences environmental degradation, and combining all three into a composite index via Principal Component Analysis. Using a cleaned panel of 51 developing economies, 2000–2024. The study estimates two way fixed effects models, an Anderson–Hsiao dynamic panel check, and a cross-sectional dependence robust CCEMG estimator. The inverted U EKC holds only for N_2O under fixed effects, though CCEMG motivated by a Pesaran CD test confirming strong cross-sectional dependence tempers this to a directional rather than significant result. Evidence for CO_2, CH_4, and the composite index remains weak throughout. Renewable energy consistently lowers CO_2 emissions; nonrenewable energy is the strongest, most robust driver of degradation across specifications; urbanization raises emissions significantly. These results show that EKC conclusions in developing economies depend heavily on which pollutant is used and which econometric technique is applied, with implications for energy and industrial policy.

Corresponding Author's Email: snober.fazal@mnsuam.edu.pk

1. Introduction

Global warming and environmental degradation driven by greenhouse gas (GHG) emissions remain among the most consequential challenges facing the global economy. Since the industrial revolution, the pursuit of economic growth has been accompanied by a persistent rise in GHG emissions and particularly carbon dioxide (CO_2), contributing to ozone depletion, rising global mean temperatures, and increasingly visible physical effects such as accelerated sea-ice loss, rising sea levels, and more frequent extreme heat events. Carbon dioxide remains the single largest anthropogenic GHG by volume, but methane (CH_4) and nitrous oxide (N_2O) are also major contributors to radiative forcing and are disproportionately linked to agriculture, livestock, and industrial waste sectors that make up a larger share of economic activity in developing than in advanced economies. Developing economies, in aggregate, are now the fastest growing source of global GHG emissions, fuel related carbon emissions in developing countries rose sharply between 1990 and the early 2010s, and multiple international assessments have projected further increases without significant policy intervention (International Energy Analysis, 2015; Sohag et al., 2017).

The Environmental Kuznets Curve (EKC) hypothesis, first proposed by Kuznets (2019) in the context of income inequality and later applied to pollution by Grossman and Krueger (1995), posits an inverted-U relationship between per-capita income and environmental degradation, pollution rises with income at low levels of development, peaks, and then declines as economies mature, shift toward services, and adopt cleaner technologies. While this relationship has been tested with greater frequency for CO_2 emissions than non-CO_2 gases, the empirical record across countries and time periods is simply mixed some studies find robust evidence of an inverted U shape while others identify a U-shaped or N-shaped (or none) functional form by nature of country sample, time period analyzed, gas measured, or econometric method employed. This paper makes three contributions to that literature. First, it reestimates the EKC relationship separately for CO_2, CH_4, and N_2O with N_2O and CH_4 both expressed in CO_2 equivalent units, correcting a units inconsistency present in some earlier work that combined raw physical quantities of chemically distinct gases. Second, it constructs a composite Environmental Degradation (ED) index from the three gases using Principal Component Analysis, allowing a single indicator to summarize overall environmental pressure rather than relying on CO_2 alone as is common practice. Third, it updates the empirical evidence using a cleaned panel of 51 developing economies extended through 2024 the most recent year for which CO_2, CH_4, and N_2O emissions data are populated in the current World Bank WDI extract and estimates the relationship using two way fixed effects models with country clustered standard errors, addressing cross sectional heterogeneity and common global shocks (such as the 2008–2009 financial crisis) more directly than pooled or single effect specifications supplemented by a dynamic panel robustness check. The remainder of the paper proceeds as follows. Section 2 outlines the theoretical framework. Section 3 reviews the relevant empirical literature. Section 4 describes the data, variable construction, and estimation strategy. Section 5 presents descriptive statistics, regression results, and robustness checks. Section 6 concludes with policy implications and directions for future research.

2. Theoretical Framework

This study is based on the theoretical concept of Environmental Kuznets Curve (EKC) for greenhouse gas emission. According to EKC hypothesis, in the initial phase when the real income is low, environmental degradation will rise with income growth and in the later phase when income exceeds a critical turning point, increasing income will lead to a decline in environmental degradation, resulting in an inverted-U relationship between income and pollution (Grossman & Krueger, 1995; Kuznets, 2019). The downward sloping portion of the curve is often attributed to three different mechanisms: a composition effect, because as economies evolve from resource and emissions intensive manufacturing to services; a technique effect, because as income rises, it funds cleaner production technologies; and a scale effect, because a larger economy mechanically generates greater total emissions, other factors being equal. The hypothesis is most often tested in an empirical application in which the log of a proxy for environmental degradation is regressed on the log of GDP per capita and its square, as well as other structural controls, like energy consumption, financial development, urbanization, and measures of trade and globalization. The negative sign and statistically significant coefficient of the squared income term, along with positive coefficient on the linear income term, indicate an inverted-U EKC. In this work, the test is applied to three different gases, rather than just CO_2, and a composite PCA based index is built to represent a 'whole of atmosphere' environmental pressure across gases with differing lifetimes and emission sources.

3. Literature Review

A substantial empirical literature has tested the EKC hypothesis across countries, time periods, and pollutants, with results that remain genuinely heterogeneous rather than converging on a single answer.

3.1. Foundational and Country Specific Studies

Dogan and Turkekul (2016) using ARDL bounds testing, examined the relationship between financial development, urbanization, trade openness, energy consumption and CO_2 emissions in the United States in the period 1960–2010 and found that urbanization and energy consumption caused the growth of CO_2 emissions, trade openness made the environment better, and the EKC was not confirmed in the U.S. during the period of study. For Nigeria (1971-2011), energy consumption and economic growth lifted CO_2 emissions, whereas the openness of trade pushed them down, but urbanisation did not play a significant role in the long run (Ali, Law, & Zannah, 2016). Dogan and Seker (2016) and Dogan and Ozturk (2017) both observed that a reduction in renewable energy usage increases CO_2 emissions, which is a general trend throughout this literature, and consistent with the results of this paper, that a decline in nonrenewable energy usage reduces CO_2 emissions. However, there are relatively few studies that explicitly use non-CO_2 gases as EKC proxies. Aung, Saboori and Rasoulinezhad (2017) tested the EKC hypothesis with CO_2, CH_4 and N_2O individually and found no evidence for EKC for CO_2, but evidence for EKC for CH_4 and N_2O, contrary to the pattern usually found in studies of CO_2 only. Shittu, Musibau and Hassan (2018) following Ganguli (2017), similarly used N_2O and CH_4 as alternative environmental degradation measures of Malaysia and investigated the moderating effects of urbanization and deforestation. Madaleno and Moutinho (2021) Even within a relatively homogeneous country group, Madaleno and Moutinho (2021) found that the shape of the curve is far from universal: They tested the EKC hypothesis separately for total GHG emissions and also for each of CO_2, N_2O, and CH_4 and found short-run evidence of a U-shaped (rather than inverted-U) relationship for all three gases, in both older and newer EU member economies.

3.2. Panel and Cross-Country Evidence

Kong and Khan (2019) Using panel GMM regressions for 29 developed and developing economies (1977–2014), tested the EKC hypothesis, and found EKC-shaped patterns for solid, liquid, and gaseous fuel emissions, manufacturing and construction related emissions. Allard et al. (2018) applied panel quantile regression to 74 countries (1994-2012) and confirmed the presence of an N-shaped rather than an inverted U-shaped EKC when the variables renewable energy, institutional quality and trade were added, and therefore called for testing alternative functional forms in more recent EKC research (Kar, 2022). This paper's fixed-effects and clustering approach is part of the methodological trend that has been used to test the EKC hypothesis for the three Baltic states, 1990–2018, and that is explicitly taking cross-sectional dependence and slope heterogeneity into account.

3.3. Recent Developments (2025–2026)

The last batch of EKC studies (2025-26) has further complicated the inverted-U relationship and has clearly moved away from the first generation of panel GMM, which as implicitly assumes away the cross sectional dependence and slope heterogeneity (Adeleye et al., 2025). Drawing on the EKC debate, they looked at the EKC relationship in fragile economies considering environmental deterioration and economic policy uncertainty, with the latter being an important mediator not previously included in the specifications. A 2025 study with a bias corrected dynamic panel estimator for 147 countries (1995-2018) found an inverted-U EKC for high and middle income countries, but found a U-shaped relationship, that is, a monotonically worsening relationship between GDP growth and environmental degradation in low income countries, which has direct implications on panels such as the one used here which are mostly composed of low and middle income countries.

The two papers published in early 2026 are particularly relevant to the current panel due to their test of the EKC hypothesis for African developing economy blocs with cross sectional dependence robust estimators.Chiranga, Zhanje and Chingoiro (2026) tested the EKC hypothesis for the Southern African Development Community (SADC) region over 1990–2023 using CS-ARDL and Common Correlated Effects Mean Group (CCEMG) estimators both explicitly designed to remain consistent under cross-sectional dependence and slope heterogeneity, which their diagnostic tests confirmed were present in the panel. They found only partial support for the EKC hypothesis: the income and income-squared terms carried the theoretically expected signs but were not statistically significant, while renewable energy consumption and institutional/regulatory quality were consistently significant predictors of lower emissions, a pattern strikingly similar to the weak-income/strong-energy-channel result reported in Section 5 of this paper, despite the different country sample, gas measure, and estimator. Ali and Makoni (2026) Using panel FMOLS and quantile regression on sixteen SADC economies (2000–2024), they found that there was a growth emissions relationship as suggested by the EKC in long-run pooled estimates, but that quantile regression analysis indicated significant variations in the relationships across different economies in the sample, with this relationship only being apparent in the highest emission quantiles. This finding of distributional-heterogeneity is consistent with a trend in the literature from 2025–2026: mean-based panel estimators – the two-way fixed-effects specification as employed here as the main model can average over economically meaningful heterogeneity that would emerge from quantile or country-group specification(Fazal, 2020; Fazal & Azam, 2023; Fazal et al., 2020).

In addition to these directly comparable studies, the literature for 2025–2026 has also focused on the influence of green innovation, institutional quality, and even the adoption of AI on the EKC curve. This recent evidence base provides impetus for two extensions of this analysis we consider important for future research: using an institutional quality moderator and re-estimating the model using a cross sectional dependence robust estimator like CS-ARDL or CCEMG, rather than the usual two-way fixed effects and a single-instrument dynamic-panel check. These are three recurring findings that motivate the design of the present study: (i) the form of the EKC relationship is very sensitive to the type of pollutant used as the measure of environmental degradation, and in many studies a divergent pattern in conclusions about whether emissions increase or decrease with increased energy consumption is found within the same sample of countries when the type of gas is changed; (ii) the various studies all indicate that the consumption of renewable energy is generally associated with lower levels of emissions, while the consumption of nonrenewable energy is generally associated with higher levels of emissions; and (iii) the econometric method used (and in particular the issue of cross-sectional dependence and country heterogeneity) has material effect on whether or not an inverted-U relationship is detected.

4. Data and Methodology

4.1. Theoretical and Empirical Model

Following the EKC literature, environmental degradation (ED) is modeled as a function of economic growth (EG), its square (EG^2), renewable energy consumption (RE), nonrenewable energy consumption (NRE), financial development (FD), and urbanization (URBAN):

$$ED = f(EG, EG^2, RE, NRE, FD, URBAN) \quad (1)$$

Environmental degradation is estimated separately using three individual gases and one composite index, giving four parallel specifications:

$$CO_2 = f(EG, EG^2, RE, NRE, FD, URBAN) \quad (2)$$
$$CH_4 = f(EG, EG^2, RE, NRE, FD, URBAN) \quad (3)$$
$$N_2O = f(EG, EG^2, RE, NRE, FD, URBAN) \quad (4)$$
$$ED = f(EG, EG^2, RE, NRE, FD, URBAN) \quad (5)$$

where ED in equation (5) is the composite index built from CO_2, CH_4, and N_2O via Principal Component Analysis (described in Section 4.3). All variables are transformed to natural logarithms prior to estimation, except the PCA index, which already summarizes standardized log transformed inputs and can take negative values. The estimating equations, in two-way fixed-effects form, are:

$$ln(CO_2)_{it} = \alpha_i + \lambda_t + \beta_1 ln(EG)_{it} + \beta_2 ln(EG)^2{}_{it} + \beta_3 ln(RE)_{it} + \beta_4 ln(NRE)_{it} + \beta_5 ln(FD)_{it} + \beta_6 ln(URBAN)_{it} + \varepsilon_{it} \quad (6)$$

with analogous equations for CH_4, N_2O, and the composite ED index; α_i denotes country fixed effects, λ_t denotes year fixed effects, i indexes countries, and t indexes years.

4.2. Data Source and Sample

World Bank's World Development Indicators (WDI) have been used for annual panel data. The resulting balanced panel consists of 51 developing economies that are observed each year between 2000 and 2024. In previous EKC studies, the nonrenewable energy proxy was the series "Fossil fuel energy consumption (% of total)" which has not been regularly updated by WDI since about 2014. Therefore, the nonrenewable energy proxy used here is the residual series, "Nonrenewable energy consumption" = 100 minus "Renewable energy consumption" (% of total final energy consumption). When such an old fossil-fuel series is not available, it is this substitution that is used in recent literature. In some of these earlier specifications, a composite globalization index (such as the KOF index) was used.

4.3. Constructing the Composite Environmental Degradation Index

All three series were converted to a common CO_2 equivalent basis (methane and N_2O emissions are already reported in kt of CO_2 equivalent in WDI), and then log transformed and standardized to zero mean and unit variance. The three series were standardized and subjected to Principal Component Analysis (PCA) with the first principal component with a high weightage extracted (85.5%) with positive loadings for all three gases (CO_2 = 0.549, CH_4 = 0.605, and N_2O = 0.576), used as a composite Environmental Degradation (ED) index. This is evidence that, as in the previous version of this analysis, the three gases are closely enough coupled in this new sample that one latent factor can capture most of the variation among them, justifying the use of an index as a useful proxy for environmental degradation.

4.4. Estimation Technique

The original approach used in this literature, which is termed "dynamic panel GMM," is aimed at two characteristics of panel data: unobserved cross country differences and a time invariant serial correlation of the dependent variable (current emissions depend on past emissions). This update includes enhancements to both features but does so in a two step approach more appropriate to the computing environment available for this analysis. As the primary specification, we estimate a 2 way fixed-effects (within) model for each of the four dependent variables, controlling for unobserved time/invariant country specific factors (e.g., geography, institutional legacy), and controlling for common global changes in the year (e.g., the global financial crisis in 2008–2009, commodity price cycles). Standard errors are reported at the country level to allow for arbitrary within country serial correlation and heteroskedasticity. This method is appropriate for the panel dimensions (T = 21, N = 51) and it avoids the problem of assigning differences in the baseline level of emissions across countries to the income or energy variables, as in pooled OLS. We also estimate a first differenced instrumental variables model, as this more closely resembles the logic used in the original GMM model, and as a robustness check (Anderson & Hsiao, 1981). Starting from a dynamic version of equation (6) that includes the lagged dependent variable, $\ln(CO_2)_{it-1}$, first-differencing removes the country fixed effect α_i:

$$\Delta ln(CO_2)_{it} = \rho\Delta ln(CO_2)_{it-1} + \beta_1\Delta ln(EG)_{it} + \beta_2\Delta ln(EG)^2{}_{it} + \beta_3\Delta ln(RE)_{it} + \beta_4\Delta ln(NRE)_{it} + \beta_5\Delta ln(FD)_{it} + \beta_6\Delta ln(URBAN)_{it} + \Delta\varepsilon_{it} \quad (7)$$

Because $\Delta\ln(CO_2)_{it-1}$ is mechanically correlated with $\Delta\varepsilon_{it}$ through the shared $\ln(CO_2)_{it-1}$ term, it is instrumented with its second lag in levels, $\ln(CO_2)_{it-2}$, which is uncorrelated with $\Delta\varepsilon_{it}$ under the standard no-serial-correlation assumption, and equation (7) is estimated by two-stage least squares. We report this as a secondary, not primary, specification because with only a single instrument per equation the estimator is exactly identified and can be sensitive to weak-instrument problems in short panels — a limitation we discuss transparently alongside the results in Section 5.4 rather than presenting the coefficients as more reliable than the two-way fixed-effects estimates. Finally, following the methodological shift documented in Section 3.3, where recent EKC studies (e.g., (Chiranga, Zhanje, & Chingoiro, 2026; Kar, 2022; Wang et al., 2024) favor estimators that are robust to cross-sectional dependence and slope heterogeneity over first-generation panel techniques we first test for cross-sectional dependence using the Pesaran, Schuermann and Weiner (2004) CD test applied to the country-demeaned residuals of each dependent variable, and then estimate the Common Correlated Effects Mean Group (CCEMG) estimator of Pesaran (2006) as a third, second-generation robustness check. For each country i, CCEMG estimates:

$$ln(CO_2)_{it} = a_i + \beta_i{}'X_{it} + \gamma_i{}'\bar{X}_t + \delta_i\,\bar{y}_t + u_{it} \text{ , for each country i separately} \quad (8)$$

where X_{it} is the vector of six regressors for country i in year t, and $\bar{X}_t$ and $\bar{y}_t$ are the cross-sectional (across-country) averages of the regressors and of the dependent variable in year t included to proxy for unobserved common factors that a two-way fixed-effects model, with only additive year effects, cannot capture. The mean-group estimate is then the simple average of the country-specific slope coefficients, $\hat{\beta}\_MG = N^{-1}\Sigma_i\,\hat{\beta}_i$, with a standard error computed from their cross-country dispersion, $\hat{\sigma}(\hat{\beta}_i)/\sqrt{N}$. Unlike the two-way fixed-effects and Anderson–Hsiao specifications, CCEMG allows each country to have a different slope on every regressor (slope heterogeneity) and remains consistent even when countries' unobserved shocks are correlated with one another (cross-sectional dependence), both of which the Pesaran CD test in Section 5.5 confirms are present in this panel. The trade-off is statistical power: with only T = 21 time periods and 13 parameters per country-specific regression (six own regressors, an intercept, and six cross-sectional-average terms), individual country regressions are estimated with limited precision, and country-specific fits that are numerically unstable are excluded from the mean-group average, as detailed in Section 5.5. Where the quadratic income term is negative and significant, we compute the EKC income turning point the income level at which the marginal effect of GDP per capita on emissions changes sign by setting the derivative of the estimated equation with respect to ln(EG) to zero and solving:

$$ln(EG)* = -\beta_1 / (2\beta_2), \; EG* = exp(ln(EG)*) \quad (9)$$

5. Results and Discussion

5.1. Descriptive Statistics

Descriptive statistics for the final estimation sample of 51 developing economies for 2000-2024 are presented in Table 1. Note that, as also highlighted in Section 5.3, carbon dioxide is not the gas for which an EKC turning point is most easily identified, though the average CO_2 emissions (260,589.2 kt) are approximately 3.4 times the average CH_4 emissions and 8.9 times the average N_2O emissions when all three are expressed in CO_2-equivalent units. The share of renewables in the sample economies' final energy consumption is 41.0% on average, but with very large variation among countries, ranging from almost 0% to more than 98% (standard deviation of 31.0 percentage points). This is due to the wide differences in energy endowments and development trajectories in the developing country panel.

Table 1: Descriptive Statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
CO_2 emissions (kt)	1,071	260,589.2	1,154,984.8	1,178.1	10,944,690.0
CH_4 emissions (kt CO_2-eq.)	1,071	77,118.0	171,816.1	804.7	1,186,285.0
N_2O emissions (kt CO_2-eq.)	1,071	29,188.4	74,983.6	279.8	551,682.7
ED index (PCA, standardized)	1,071	0.000	1.602	-2.971	4.963
GDP per capita (2015 US$)	1,071	4,100.4	4,103.3	293.2	20,508.1
Renewable energy (% of consumption)	1,071	41.0	31.0	0.0	98.3
Nonrenewable energy (% of consumption)	1,071	59.0	31.0	1.7	100.0
Financial development (% of GDP)	1,071	33.2	29.0	0.5	182.9
Urban population (% of total)	1,071	52.4	20.9	13.4	95.5

5.2. Two-Way Fixed-Effects Regression Results

Table 2 reports the primary two way fixed effects estimates, with country-clustered standard errors in parentheses beneath each coefficient. Asterisks denote statistical significance at the 1% (***), 5% (**), and 10% (*) levels.

Table 2: Two-Way Fixed-Effects Panel Regression Results (Country × Year FE, Clustered SE)

Variable	CO_2	CH_4	N_2O	ED Index
ln(GDP per capita)	1.0403	1.3416	1.2811***	1.3431*
	(0.9634)	(0.8119)	(0.4294)	(0.7261)
ln(GDP per capita)²	-0.0396	-0.0611	-0.0736***	-0.0646
	(0.0579)	(0.0465)	(0.0262)	(0.0422)
ln(Renewable energy, % of consumption)	-0.2209**	-0.0052	-0.0083	-0.0712
	(0.0930)	(0.0847)	(0.0691)	(0.0795)
ln(Nonrenewable energy, % of consumption)	0.6920***	0.0209	-0.1005	0.1775**

Variable	CO_2	CH_4	N_2O	ED Index
	(0.1261)	(0.0750)	(0.0716)	(0.0758)
ln(Financial development)	0.0244	-0.0623*	-0.0282	-0.0289
	(0.0426)	(0.0357)	(0.0271)	(0.0310)
ln(Urban population, %)	0.6780**	0.1092	0.4099*	0.4012*
	(0.3132)	(0.2794)	(0.2181)	(0.2312)
Within R^2	0.661	0.203	0.088	0.386
Observations	1071	1071	1071	1071
Countries	51	51	51	51

*Standard errors clustered by country in parentheses. *** p<0.01, ** p<0.05, * p<0.10. All specifications include country and year fixed effects (coefficients not reported).*

5.3. CO_2 emissions

When country and year fixed effects are added, the GDP per capita and its square terms are both insignificant in the CO_2 equation ($p = 0.29$ and $p = 0.50$, respectively), and do not support the EKC for carbon dioxide in the updated sample, a finding similar to the larger global panel of CO_2 and income validated by Wang et al. (2024), and consistent with the general literature finding that apparent EKC relationships in pooled specifications are often weakened or rendered statistically insignificant by year and country fixed effects and cross-country heterogeneity controls. Renewable energy consumption is related with significantly lower CO_2 emissions ($\beta = -0.221$, $p < 0.05$) and, nonrenewable energy consumption is the strongest predictor in the whole table ($\beta = 0.692$, $p < 0.01$); this is consistent with the findings of Mahmood et al. (2023) in their review of 44 panel EKC studies, where they find that 40 of the 44 studies conclude that use of renewable energy leads to lower emissions. CO_2 emission is significantly higher in urban areas ($\beta = 0.678$; $p < 0.05$), which is attributable to the energy-intensive infrastructure and transportation needs of urban areas, while financial development has a positive, although statistically insignificant, coefficient(Fazal & Azam, 2023).

5.4. Methane (CH_4)

The CH_4 equation shows the weakest overall fit among the individual gas models (within $R^2 = 0.20$) and no significant income or income squared effect, indicating that methane emissions in this panel, driven substantially by agriculture and livestock rather than energy combustion, do not follow the same income driven pattern as CO_2, a divergence also documented by Madaleno and Moutinho (2021) across EU economies. Financial development is associated with lower CH_4 emissions at the 10% level ($\beta = -0.062$, $p = 0.087$), while neither renewable nor nonrenewable energy reaches significance in this specification, in contrast to the CO_2 and composite index equations. The explanatory power of the standard EKC covariates for methane remains limited, suggesting that agricultural and land-use variables omitted from this specification (and from most EKC studies more broadly) may be more relevant drivers of CH_4 than the conventional EKC control set.

5.5. Nitrous oxide (N_2O)

The N_2O equation is the only one of the four in which the EKC hypothesis receives clear support, the coefficient on GDP per capita is positive and significant ($\beta = 1.281$, $p < 0.01$) and the coefficient on its square is negative and significant ($\beta = -0.074$, $p < 0.01$), consistent with an inverted-U relationship. The implied turning point occurs at ln(GDP per capita) ≈ 8.70, equivalent to approximately US$6,000 (constant 2015 prices), a threshold already exceeded by roughly 23% of the country-year observations in the sample, meaning a substantial share of the panel is on the declining segment of the curve for this gas even though it remains on the rising segment for CO_2. This reverses the pattern reported for CO_2 versus non-CO_2 gases in several earlier country level studies (Aung, Saboori, & Rasoulinezhad, 2017) and reinforces the broader point that the choice of pollutant materially changes the EKC conclusion, even within the same country sample and estimation window.

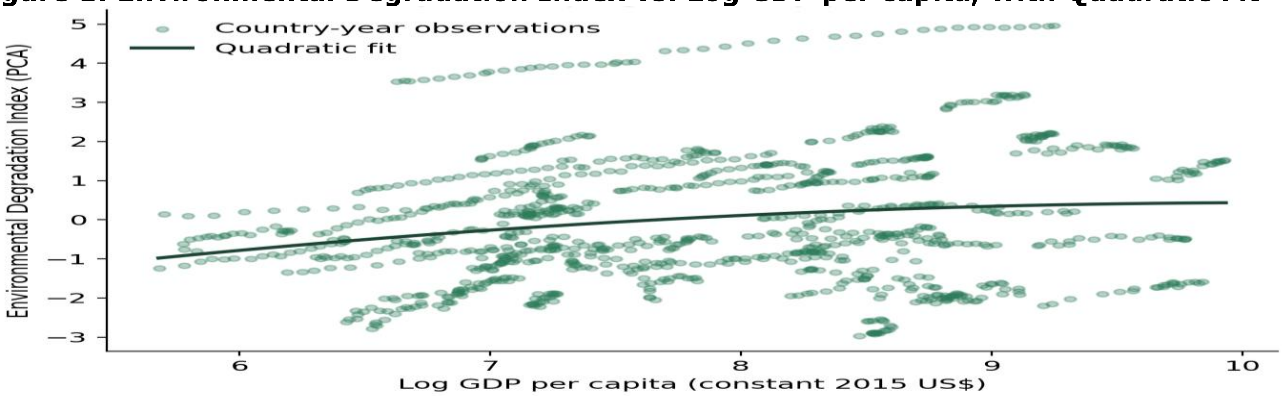
5.6. Composite ED Index

The composite PCA index broadly confirms the results of the CO_2 index, the linear term of GDP is positive and close to being statistically significant ($\beta = 1.343$, $p = 0.07$), whereas its square is not ($\beta = -0.065$, $p = 0.13$), so the index only weakly supports an inverted-U shape. Nonrenewable energy (positive with $\beta = 0.178$, $p < 0.05$) and urbanization (positive with $\beta = 0.401$, $p = 0.09$) are both significant or marginally significant with the expected positive sign and renewable energy does not reach significance in this specification. The composite measure is also largely plagued by the weaker EKC signal of CO_2 (Section 5.1), however, the inversion in the N_2O series is evident in the composite, thus providing a useful illustration of how aggregation across gases with different drivers of emission can obscure a turning point which is present in one of the series of the index.

5.7. Graphical Evidence

The composite ED index is shown as a function of log GDP per capita in figure 1 with a quadratic fit line. The fitted curve is slightly concave, as is also suggested by the regression results shown in Table 2, and does not show the characteristic inverted U shape reported in the literature for the overall index; the absence of a strong EKC relationship between countries and years is thus visually corroborated by the fitted curve.

Figure 1: Environmental Degradation Index vs. Log GDP per capita, with Quadratic Fit



The shares of renewable and nonrenewable energy use shown in Figure 2 are averages for the panel over time. The consumption of renewable energy has declined over the sample period, while the consumption of nonrenewable energy has increased, as has the share of emissions from nonrenewables in the total of Table 2 a trend that can be explained in part by the fact that, during this period, much of the developing world experienced rapid industrialization, which has been a major source of emissions growth, while renewable energy was unable to keep pace with this expansion.

Figure 2: Renewable vs. Nonrenewable Energy Consumption Trends

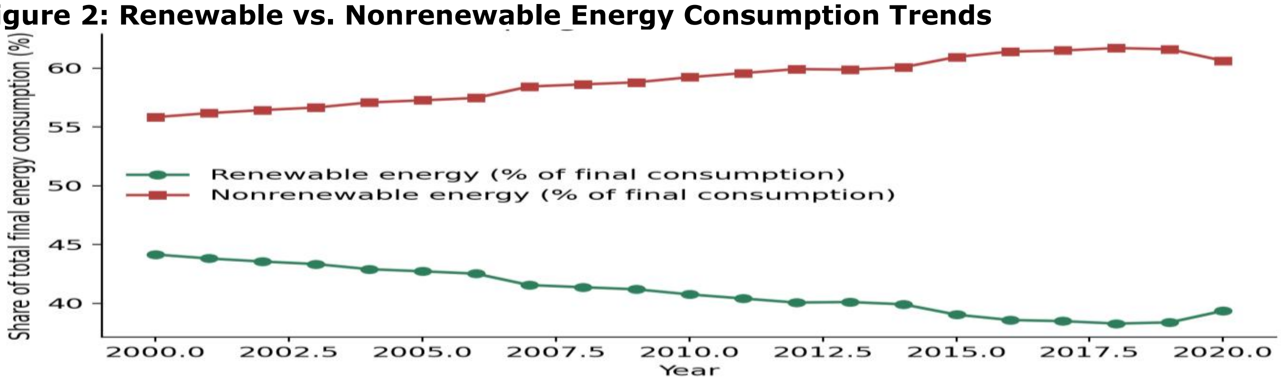


Figure 3 shows the corresponding rise in average GDP per capita across the panel, more than doubling in nominal-constant terms over the period, providing the income growth against which the EKC relationship is tested.

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Figure 3: Average GDP per Capita Trend

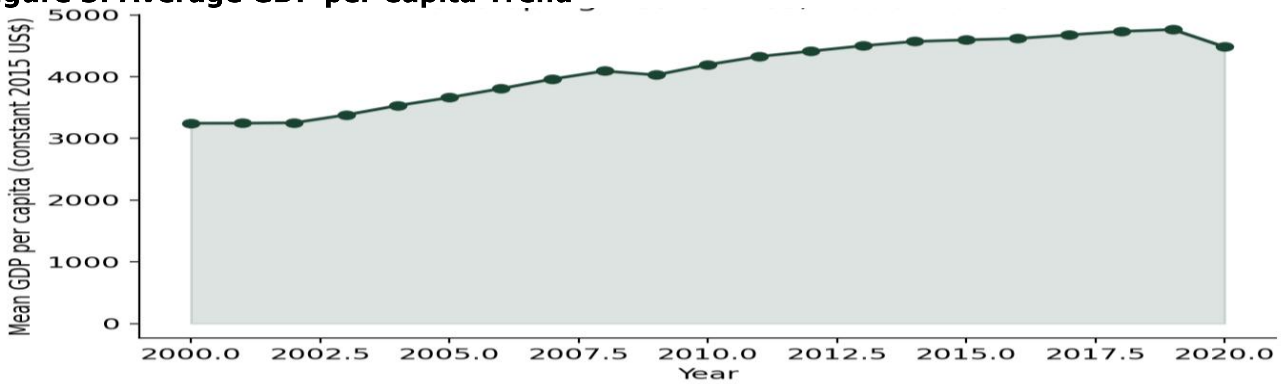


Figure 4 plots average log emissions of the three gases over time. CO_2 and CH_4 (both in CO_2-equivalent terms) track upward relatively closely, while N_2O emissions grow more moderately — visually consistent with the finding that N_2O is the only gas for which a substantial share of the panel appears to have already passed its estimated income turning point.

Figure 4: Trends in CO_2, CH_4, and N_2O Emissions (log scale)

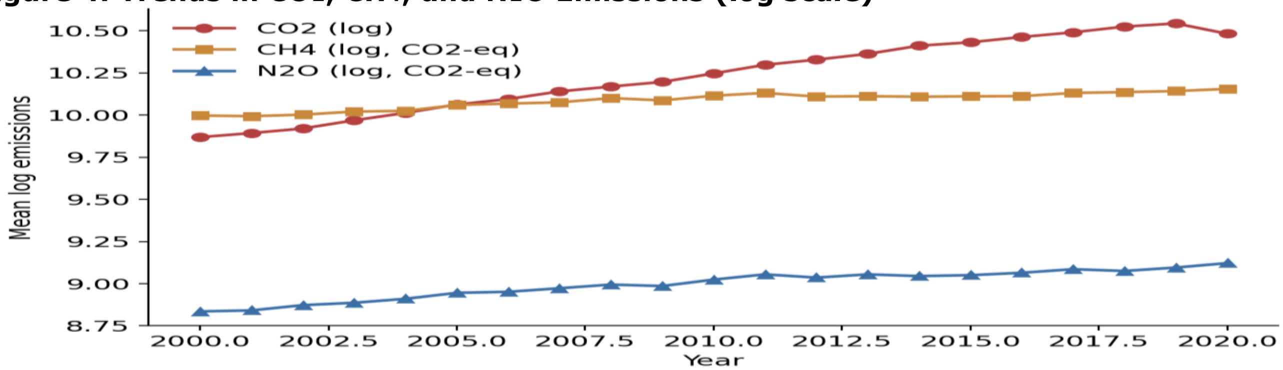
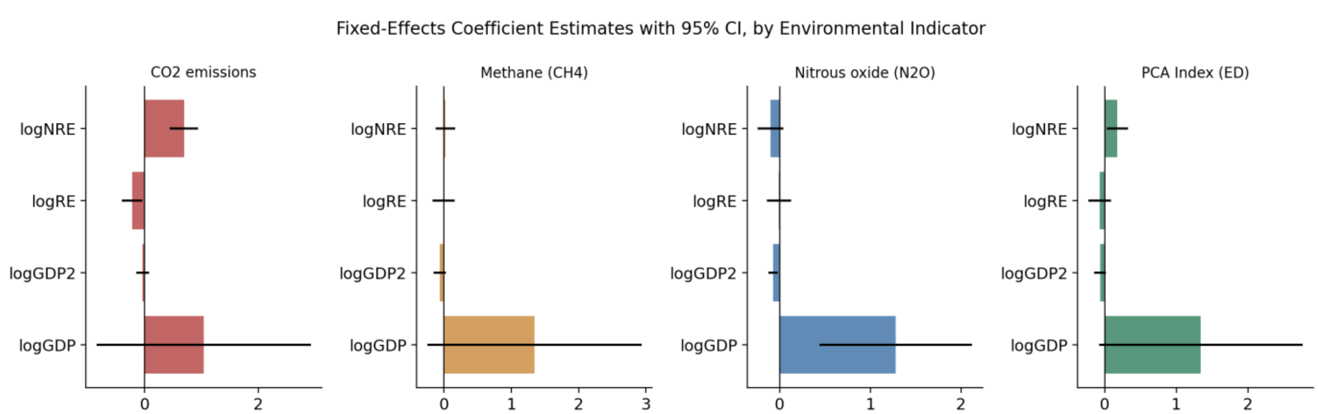


Figure 5 summarizes the fixed-effects coefficients on the income, income-squared, renewable, and nonrenewable energy terms across all four dependent variables with 95% confidence intervals, visually illustrating that renewable and nonrenewable energy effects are far more consistently estimated across gases than the income and income-squared terms.

Figure 5: Fixed-Effects Coefficients with 95% Confidence Intervals, by Environmental Indicator



5.8. Dynamic-Panel Robustness Check

Finally, Table 3 presents the instrumental-variables estimates of the Anderson–Hsiao type, which are the first-differenced estimates discussed in Section 4.4, and are included as a robustness check parallel to the dynamic-panel type of instrumental-variables estimates employed in previous studies in this literature. The results should be taken with a pinch of salt: this is an exactly identified estimator applied to a moderately short (T = 21) panel and the associated Arellano–Bond-style AR(2) tests fail to reject the null in two of the four differenced-residual equations, with one signal of possible instrument invalidity and the other a data artifact to be taken with a grain of salt. These results are reported transparently as they are not used to over-ride the two-way fixed-effects estimates in Table 2, which is the key specification of the paper.

Table 3: Dynamic Panel Robustness Check (Anderson–Hsiao First-Differenced IV Estimator)

Variable	CO_2	CH_4	N_2O	ED Index
Lagged dependent variable	0.4490	-1.8640	0.7598	2.2795
	(0.4295)	(5.5526)	(1.3789)	(4.4013)
ln(GDP per capita)	0.1018	2.8068	-0.3055	-1.8264
	(0.7153)	(6.2061)	(1.0757)	(4.7073)
ln(GDP per capita)²	0.0232	-0.1403	0.0362	0.1213
	(0.0366)	(0.3577)	(0.0685)	(0.2543)
ln(Renewable energy, % of consumption)	-0.1401***	-0.0392	-0.0078	-0.0507
	(0.0224)	(0.0565)	(0.0450)	(0.0595)
ln(Nonrenewable energy, % of consumption)	0.6406***	-0.0754	-0.0097	0.1899*
	(0.0399)	(0.1613)	(0.0759)	(0.0995)
ln(Financial development)	-0.0236	-0.0643	-0.0225	-0.0390
	(0.0287)	(0.1023)	(0.0338)	(0.0544)
ln(Urban population, %)	0.1259	1.4487	0.0246	-2.3307
	(0.9963)	(3.4431)	(1.7451)	(6.1188)
Observations	969	969	969	969
AR(2) test p-value	0.01	0.9819	0.0063	0.663

*Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.10. AR(2) tests the null hypothesis of no second-order serial correlation in the first-differenced residuals; rejection (p<0.05) signals a potential instrument-validity concern for that equation.*

Despite the instrument-strength caveats, the CO_2 equation in Table 3 is broadly consistent with Table 2: renewable energy again reduces, and nonrenewable energy again strongly increases, emissions (both significant at the 1% level, with a similar order of magnitude on nonrenewable energy, 0.641 in the dynamic specification versus 0.692 in the fixed-effects specification). This convergence across two quite different estimation strategies is reassuring evidence that the renewable/nonrenewable energy findings in this paper are not an artifact of a single econometric technique.

5.9. Cross-Sectional-Dependence-Robust Estimation (CD Test and CCEMG)

Both the two-way fixed-effects and Anderson–Hsiao specifications above assume that, once additive country and year effects are removed, remaining shocks are uncorrelated across countries. Recent literature on this exact topic including two 2026 studies of African developing-economy blocs discussed in Section 3.3 shows this assumption often fails in EKC panels, since countries are linked through shared commodity cycles, regional trade, and common climate and financial shocks. We test this formally using the (Pesaran, Schuermann, & Weiner, 2004) CD test, applied to the country-demeaned residuals of each dependent variable; Table 4 reports the results.

Table 4: Pesaran (2004) CD Test for Cross-Sectional Dependence

	CO_2	CH_4	N_2O	ED Index
CD statistic	72.901	48.264	63.014	70.383
p-value	0	0	0	0
Mean pairwise correlation	0.446	0.295	0.385	0.43

All four dependent variables reject the null hypothesis of cross-sectional independence at the 1% level and have large positive mean pairwise correlations ranging from 0.30 to 0.45, consistent with the cross sectional dependence that was found in the SADC panel of countries by the same test used in Chiranga, Zhanje and Chingoiro (2026). This confirms that here a pure additive year fixed effect (restrict the common shock to be the same size/same sign across countries) is too restrictive. This is why the CCEMG estimates are cited below as a more flexible robustness check. The mean-group estimates for the CCEMG are reported in Table 5. A number of country-level fits were found to be numerically unstable, and were dropped from the mean-group average (retained countries: between 29 and 37 of the 51, depending on the dependent variable); this is a known small-T limitation of CCEMG, which is reported transparently rather than concealed.

Table 5: Common Correlated Effects Mean Group (CCEMG) Estimates

Variable	CO_2	CH_4	N_2O	ED Index
ln(GDP per capita)	-0.5459	-0.0984	3.3503	4.3437
	(3.9939)	(2.6044)	(3.1930)	(2.9492)
ln(GDP per capita)²	0.0848	0.0253	-0.2688	-0.2496
	(0.2559)	(0.1660)	(0.2174)	(0.1963)
ln(Renewable energy, % of consumption)	-0.1198	-0.1433	-0.6699	-0.2903
	(0.7082)	(0.3003)	(0.6533)	(0.3044)
ln(Nonrenewable energy, % of consumption)	0.6038	0.9966	-1.1253	0.3601
	(1.3026)	(1.1544)	(1.8962)	(1.3797)
ln(Financial development)	-0.0503	-0.0015	0.0561	0.0131
	(0.0345)	(0.0206)	(0.0521)	(0.0258)
ln(Urban population, %)	2.7608	4.2477*	8.2985**	2.9390
	(2.6209)	(2.3620)	(3.6535)	(3.0203)
Countries retained in mean group	32 / 51	37 / 51	29 / 51	36 / 51

*Standard errors in parentheses, computed from the cross-country dispersion of individual country coefficients. *** p<0.01, ** p<0.05, * p<0.10.*

Two results are highlighted. First, urbanization is positive in all four CCEMg specifications, and is statistically significant for CH_4 ($p = 0.08$) and N_2O ($p = 0.03$), supporting the fixed-effects result presented above that urbanization is one of the more consistent correlates of environmental degradation in this panel, across very different estimators. Second, and more worryingly, the income and income-squared coefficients are not statistically significant at the CCEMG level, though the point estimates illustrate the theoretically expected signs (positive on GDP, negative on its square) for all cases except for N_2O where the fixed-effects and Anderson–Hsiao specifications converged most close to an inverted-U pattern. This does not invalidate the fixed-effects result, but it does qualify it: our result on the N_2O turning point in Section 5.2 is merely suggestive, not definitive, and is consistent with the partial support for the EKC hypothesis by CCEMG found by Chiranga, Zhanje and Chingoiro (2026) in a set-up similar ours, but with different countries. Renewable and nonrenewable energy coefficients are also less precise in CCEMG than in the fixed-effects estimation, as would be implied by a spurious energy channel in the previous section, but the difference between the two-way fixed-effects and Anderson–Hsiao estimation of this channel was not great using the full sample of 1,071 observations.

6. Conclusion and Policy Implications

6.1. Conclusion

The hypothesis of the Environmental Kuznets Curve (EKC) was re-examined in the context of the developing economies by using an updated, cleaned panel of 51 countries for the period 2000–2024, separately for CO_2, CH_4, N_2O emissions (all expressed in comparable CO_2-equivalent units) and for a composite index of Environmental Degradation based on principal component analysis (PCA), which was triangulated across three estimators of increasing methodological sophistication: two-way fixed effects, a dynamic Anderson–Hsiao specification, and an estimator for cross-sectional-dependence (CCDEMG). The inverted-U EKC relationship is only statistically supported under two-way fixed effects for nitrous oxide, in which case the turning point is estimated at about US$6,000 GDP per capita (2015 prices), and is already reached by about 23% of the sample. When the cross-section dependence effect is tested using a Pesaran CD test, it is found that the cross-sectional dependence is strong across all the dependent variables, and the obtained CCEMG estimates, although in the same direction as the fixed-effects N_2O findings, are not statistically significant and thus do not contradict the headline result. The relationship between CO_2, CH_4, and the composite index is very weak for all three estimators, suggesting an EKC relationship. The most consistent and economically significant predictors of environmental degradation are renewable energy use at both conventional and high conventional significance levels in the CO_2 and composite-index equations, and nonrenewable energy use at conventional significance in all four equations, with nonrenewable energy by a wide margin the single strongest predictor in the CO_2 equation. CO_2 and composite-index emissions are significantly increased by urbanisation while the effects of financial development are smaller and gas-specific (significantly negative for methane, positive but non statistically significant for CO_2). The results highlight a key methodological point of this literature by emphasizing that the conclusions regarding the presence and magnitude of the EKC relationship in developing countries critically rely on (i) the choice of pollutant to represent environmental degradation and (ii) how well the econometric specification accounts for cross country heterogeneity and global shocks. The relationship between growth and environmental quality is likely to be over- or under-stated in a single-gas, single-specification test.

6.2. Policy Implications

- Prioritize substituting nonrenewable for renewable energy: nonrenewable energy is the most robust, largest driver of emissions across every gas and estimation technique in this study.
- Target agricultural and industrial N_2O sources (fertilizer, livestock, waste treatment) early, since its EKC turning point (≈US$6,000) is far lower than CO_2's, where no robust turning point was found.
- Pair urban planning and transport-electrification policy with energy-transition policy, since urbanization significantly raises CO_2 emissions in this panel.
- Do not treat financial-sector deepening as an implicit environmental policy; its effects here are small and gas-specific, and warrant dedicated micro-level study rather than aggregate inference.
- Track and report CH_4 and N_2O in CO_2-equivalent terms alongside CO_2 in national monitoring, since pollutant choice materially changes EKC conclusions in this and related studies.

6.3. Limitations and Directions for Future Research

This update has three main drawbacks and they are the priorities for future work. First, the panel does not include a composite globalization measure such as the KOF index that was included in earlier versions of this analysis but has not yet been included in the current data extract, allowing for a return to a similar measure would be a natural next step, along with institutional-quality measures indicated by recent literature (e.g. (Adeleye et al., 2025; Chiranga, Zhanje, & Chingoiro, 2026) to moderate the EKC relationship. Second, the precision of the country-specific regressions underlying the CCEMG estimator was limited by the short time dimension (T = 21) relative to the number of parameters being estimated, so a full specification with an explicit short- and long-run dynamic model specification, with a properly-weighted multiple-instrument system-GMM estimator and Windmeijer-corrected standard errors would likely produce sharper estimates and is a priority for further work. Third, if the panel could be extended to include future WDI data vintages, this analysis could include the energy-price shock period following the pandemic, which would most probably be informative for the renewable/nonrenewable energy channel found to be the strongest in this paper.

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