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Economic Growth and Environmental Degradation: A Panel Data Analysis of Carbon Emissions and GDP Across Developing Countries

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Abstract

The relationship between economic growth and environmental degradation remains a critical issue for developing countries that seek to sustain economic expansion while reducing carbon emissions. Grounded in the Environmental Kuznets Curve (EKC) hypothesis, this article examines the relationship between carbon dioxide (CO_2) emissions and gross domestic product (GDP) per capita across 65 developing countries during 2000-2022. The empirical analysis applies panel data estimation techniques, including Fixed Effects, Random Effects, the Hausman specification test, and System Generalized Method of Moments (System GMM) to address potential endogeneity. Energy consumption, renewable energy share, foreign direct investment (FDI), and trade openness are included as control variables. The findings support the EKC hypothesis. GDP per capita has a positive and significant effect on CO_2 emissions, while the squared term of GDP per capita has a negative and significant effect, confirming an inverted U-shaped relationship. The estimated turning point of approximately US$8,742 per capita indicates that many developing countries remain in the growth phase where emissions continue to rise. Energy consumption is the strongest positive driver of emissions, whereas renewable energy share significantly reduces environmental degradation. FDI shows a positive but statistically insignificant effect, while trade openness significantly increases emissions. System GMM estimation confirms the robustness of the results after controlling for endogeneity and emissions persistence. These findings highlight the need for renewable energy transition, stronger environmental governance, and trade-investment policies that support green growth in developing economies.

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1. INTRODUCTION

Economic growth and environmental degradation remain central concerns in contemporary environmental economics, particularly in developing countries where industrial expansion, urbanization, and energy demand continue to increase simultaneously. The acceleration of economic activity has improved income levels and production capacity, yet it has also intensified pressure on natural systems through higher carbon dioxide (CO_2) emissions, fossil fuel dependence, and resource-intensive development patterns. The urgency of this issue is reinforced by global climate assessments showing that sustained greenhouse gas emissions continue to increase climate-related risks, with developing countries often facing greater vulnerability because of limited adaptive capacity and weaker environmental infrastructure (Change, 2023), (Friedlingstein et al., 2025).

A major theoretical framework for explaining the relationship between income growth and environmental pressure is the Environmental Kuznets Curve (EKC). The EKC hypothesis argues that environmental degradation tends to rise during the early stages of economic development, but after a certain income threshold, further economic growth may reduce pollution through technological progress, structural transformation, stronger regulation, and higher public demand for environmental quality (Grossman & Krueger, 1991), (Kuznets, 1955). In this framework, the relationship between GDP per capita and CO_2 emissions is expected to follow an inverted U-shaped pattern. However, the empirical validity of this hypothesis remains debated, especially in developing countries where economic structures, energy systems, institutional quality, and trade patterns differ substantially from those of advanced economies (Han & Jun, 2023), (Kong & Khan, 2019).

Developing countries often face a more complex growth, environment trade-off. Many still rely heavily on fossil fuels to support manufacturing, transportation, electricity generation, and infrastructure development. The (Agency, 2023) emphasizes that the global energy system remains shaped by uneven transitions, where emerging and developing economies require substantial investment to shift toward cleaner and more secure energy systems. At the same time, World Bank development indicators show that GDP, energy consumption, trade openness, FDI inflows, and CO_2 emissions remain closely connected in many low- and middle-income economies (Bank, 2024). These conditions make developing countries a critical context for reassessing whether economic growth can eventually decouple from environmental degradation.

The role of renewable energy is increasingly important within the EKC framework. Renewable energy can reduce dependence on fossil fuels and weaken the positive relationship between economic growth and emissions. Recent empirical evidence suggests that renewable energy adoption contributes to lower CO_2 emissions and supports more sustainable economic development, although the magnitude of the effect varies across country groups, institutional settings, and levels of energy dependence (Kayani et al., 2024), (Naseem et al., 2023), (Jie & Rabnawaz, 2024). Therefore, incorporating renewable energy share into the growth–emissions model is essential to evaluate whether developing countries can shift from emission-intensive growth toward greener development pathways.

Foreign direct investment and trade openness also play important roles in shaping environmental outcomes. On one hand, FDI may support cleaner production through technology transfer, management improvement, and international environmental standards, consistent with the pollution halo hypothesis. On the other hand, FDI may increase emissions if multinational firms relocate pollution-intensive activities to countries with weaker environmental regulations, consistent with the pollution haven hypothesis (Copeland & Taylor, 2004), (Dilanchiev et al., 2024), (Sarkodie & Strezov, 2019). Trade openness can also generate competing effects. It may improve access to cleaner technologies and more efficient production systems, but it can also expand the scale of output and reinforce specialization in emission-intensive sectors. These competing mechanisms make the environmental effects of FDI and trade highly dependent on country-specific conditions.

Although the EKC literature is extensive, several gaps remain. First, many empirical studies focus on developed economies, OECD countries, or specific groups such as BRICS, leaving broader panels of developing countries relatively underexplored. Second, several studies rely heavily on static panel estimators, even though the relationship between income growth and CO_2 emissions may involve endogeneity, dynamic persistence, and reverse causality. Third, the combined roles of energy consumption, renewable energy, FDI, and trade openness are often examined separately, limiting the ability to understand the broader structural determinants of emissions. Addressing these gaps requires an empirical framework that integrates static panel models with dynamic panel estimation techniques.

This article contributes to the literature by examining the relationship between GDP per capita and CO_2 emissions across 65 developing countries over the period 2000-2022. The analysis applies Fixed Effects and Random Effects estimators, the Hausman specification test, and System Generalized Method of Moments to address endogeneity and dynamic persistence in emissions. Energy consumption, renewable energy share, FDI inflows, and trade openness are incorporated as control variables to provide a more comprehensive explanation of environmental degradation in developing economies. By combining updated data, a broad developing-country sample, and dynamic panel estimation, this article offers empirical evidence relevant for green growth policy, renewable energy transition, and sustainable development planning.

2. LITERATURE REVIEW

2.1 Environmental Kuznets Curve and the Growth–Emissions Nexus

The Environmental Kuznets Curve originates from (Kuznets, 1955) argument that income inequality may initially increase and later decline as economies develop. (Grossman & Krueger, 1991) extended this logic to environmental outcomes by suggesting that pollution may rise during the early phase of development and decline after countries reach a higher income level. The EKC mechanism is generally explained through three channels: scale effect, composition effect, and technique effect. The scale effect indicates that economic expansion increases production and emissions. The composition effect refers to structural transformation from pollution-intensive sectors toward cleaner industries and services. The technique effect reflects improvements in technology, energy efficiency, and environmental regulation.

Empirical findings on the EKC remain mixed. (Kong & Khan, 2019) provide evidence that economic growth and environmental pollution may follow an EKC pattern across developed and developing countries, although the strength of the relationship differs by country characteristics. (Han & Jun, 2023) revisits the EKC framework using a large panel of countries and highlights the importance of renewable energy and climate finance in explaining the growth, emissions relationship. (Osei & Kim, 2023) further show that income, energy use, and carbon emissions remain closely connected across regions, confirming that economic development and environmental pressure are not independent processes.

The mixed results in the EKC literature suggest that the relationship between GDP per capita and CO_2 emissions depends on model specification, estimation method, sample composition, and the inclusion of relevant control variables. In developing countries, the EKC may not emerge automatically because many economies remain dependent on fossil fuels, have weaker environmental regulation, and continue to expand emission-intensive sectors. Therefore, testing the EKC in a broad panel of developing countries requires attention not only to GDP and its squared term, but also to energy consumption, renewable energy, FDI, and trade openness.

2.2 Energy Consumption, Renewable Energy, and Carbon Emissions

Energy consumption is one of the most important determinants of CO_2 emissions. Fossil fuel combustion in electricity generation, transportation, industry, and household energy use contributes directly to carbon emissions. In developing countries, rapid urbanization and industrialization increase energy demand, while energy systems often remain dominated by coal, oil, and natural gas. The International Energy Agency (2023) emphasizes that global energy transitions are progressing, but emerging and developing economies still require significant investment to achieve cleaner energy systems.

Renewable energy is widely regarded as a key instrument for reducing emissions while maintaining economic development. (Jie & Rabnawaz, 2024) show that renewable energy is closely related to GDP growth and CO_2 emissions in both developing and developed countries, indicating that renewable energy can support a transition toward lower-carbon development. (Kayani et al., 2024) also demonstrate that renewable energy, technological innovation, globalization, and FDI are important factors in explaining carbon emissions among BRICS countries. Similarly, (Naseem et al., 2023) find that renewable energy and sustainable FDI are relevant in reducing environmental degradation, although the effect depends on broader economic and trade conditions.

Within the EKC framework, renewable energy may strengthen the technique effect by enabling countries to produce more output with fewer emissions. However, renewable energy does not automatically reduce emissions if total energy demand grows faster than clean energy capacity. Therefore, the role of renewable energy should be examined alongside total energy consumption. A model that includes both energy consumption and renewable energy share can distinguish between the emission-increasing effect of energy demand and the emission-reducing effect of cleaner energy composition.

2.3 Foreign Direct Investment, Pollution Haven, and Pollution Halo

The environmental effect of foreign direct investment remains theoretically ambiguous. The pollution haven hypothesis suggests that multinational firms may move pollution-intensive production to developing countries with weaker environmental standards. In contrast, the pollution halo hypothesis argues that FDI may improve environmental performance by transferring cleaner technologies, better management practices, and more efficient production systems (Copeland & Taylor, 2004).

Empirical evidence supports both possibilities. (Sarkodie & Strezov, 2019) show that the effect of FDI, economic development, and energy consumption on greenhouse gas emissions differs across developing countries, indicating that the environmental impact of FDI depends on host-country conditions. (Dilanchiev et al., 2024) find that FDI, renewable energy, and remittances interact with environmental quality in complex ways, suggesting that capital inflows may either worsen or improve environmental outcomes depending on energy structure and institutional context. (Kayani et al., 2024) also report that FDI is closely connected with carbon emissions, ecological footprint, renewable energy, globalization, and technological innovation in BRICS economies.

These findings indicate that FDI should not be treated as uniformly beneficial or harmful. Its effect on emissions depends on the sector receiving investment, regulatory enforcement, technological absorptive capacity, and the degree to which host countries direct investment toward green sectors. Therefore, including FDI in the empirical model is important for assessing whether international capital inflows contribute to pollution-intensive growth or support cleaner development.

2.4 Trade Openness and Environmental Quality

Trade openness affects environmental quality through scale, composition, and technique effects. The scale effect occurs when trade expansion increases production and energy consumption, leading to higher emissions. The composition effect occurs when countries specialize in sectors where they have comparative advantage, which may increase emissions if developing countries specialize in resource-intensive or pollution-intensive production. The technique effect occurs when trade facilitates access to cleaner technologies and more efficient production processes (Copeland & Taylor, 2004).

In developing countries, trade openness may increase emissions if export growth depends on manufacturing, extractive industries, or primary commodities. However, trade may also reduce emissions if it improves technology transfer and supports the import of cleaner equipment. (Naseem et al., 2023) include trade as an important determinant of greenhouse gas emissions, while (Dilanchiev et al., 2024) show that environmental outcomes are shaped by the interaction between international financial flows, renewable energy, and macroeconomic openness. These findings suggest that the effect of trade openness is not uniform and should be examined empirically within a broader model of economic growth and environmental degradation.

For developing economies, trade policy has important environmental implications. Without strong environmental governance, trade liberalization may increase emissions through production expansion and specialization in high-emission sectors. Conversely, trade agreements that encourage clean technology, environmental standards, and green investment may help reduce the emission intensity of growth. Therefore, trade openness is a relevant control variable in the EKC model.

2.5 Dynamic Panel Estimation and Endogeneity Concerns

The relationship between GDP per capita and CO_2 emissions may suffer from endogeneity. Economic growth can increase emissions through energy use and production expansion, but environmental degradation and energy constraints may also affect economic performance. Static panel models such as Fixed Effects and Random Effects can control for unobserved heterogeneity, but they may not fully address dynamic persistence and reverse causality.

The Hausman specification test is commonly used to determine whether Fixed Effects or Random Effects is more appropriate when unobserved country-specific effects may be correlated with explanatory variables (Hausman, 1978). For dynamic panel settings, (Arellano & Bond, 1991) developed specification tests and GMM estimators suitable for models with lagged dependent variables and individual effects. (Arellano & Bover, 1995) and (Blundell & Bond, 1998) further developed the System GMM approach, which improves efficiency by combining equations in levels and first differences. (Windmeijer, 2005) provides finite-sample correction for two-step GMM standard errors, while (Roodman, 2009) highlights practical issues in System GMM estimation, including instrument proliferation, autocorrelation testing, and the validity of over-identifying restrictions.

Because CO_2 emissions often exhibit persistence over time, dynamic panel estimation is suitable for examining the growth, emissions relationship. System GMM allows lagged emissions to be included as an explanatory variable while addressing potential endogeneity in GDP per capita and other regressors. Therefore, the use of System GMM alongside static panel estimators strengthens the empirical credibility of EKC testing in developing countries.

2.6 Research Gap and Contribution

The reviewed literature shows that the EKC remains an important but contested framework for understanding the relationship between economic growth and environmental degradation. Previous studies have provided valuable evidence on GDP, energy consumption, renewable energy, FDI, and trade openness, yet several limitations remain. First, many studies focus on selected groups of countries, such as BRICS, OECD, or developed economies, which limits generalization to the broader developing-country context. Second, the interaction between economic growth, energy structure, renewable energy, FDI, and trade openness is often examined in fragmented models. Third, endogeneity and dynamic persistence are not always adequately addressed, even though emissions and income may influence each other over time.

This article addresses these gaps by analyzing 65 developing countries over the period 2000–2022 using a panel data framework that combines Fixed Effects, Random Effects, Hausman specification testing, and System GMM estimation. The model incorporates GDP per capita, squared GDP per capita, energy consumption, renewable energy share, FDI inflows, and trade openness within a unified EKC framework. This approach provides a more comprehensive assessment of whether developing countries exhibit an inverted U-shaped growth–emissions relationship and whether renewable energy can help reduce the environmental cost of economic development.

3. METHODOLOGY

3.1 Data Sources and Sample

This article employs a balanced panel dataset covering 65 developing countries across five major regions: Sub-Saharan Africa, South Asia, East Asia and the Pacific, Latin America and the Caribbean, and the Middle East and North Africa. The observation period spans 2000-2022, producing 1,495 country-year observations, with 65 cross-sectional units and 23 annual time periods.

The selection of developing countries is based on data availability and consistency across the main variables used in the empirical model. The primary data source is the World Bank's World Development Indicators, which provides internationally comparable macroeconomic, environmental, trade, and investment indicators. Energy-related variables are supplemented by the International Energy Agency, while emissions data are cross-checked with Global Carbon Budget and Our World in Data to ensure consistency in carbon emission reporting.

The dependent variable is carbon dioxide emissions per capita, measured in metric tons per person. The main explanatory variable is GDP per capita, measured in constant 2015 US dollars, and its squared term is included to test the Environmental Kuznets Curve hypothesis. The model also incorporates four control variables: energy consumption per capita, renewable energy share, foreign direct investment net inflows, and trade openness. These variables are selected because they represent the main structural channels through which economic activity may influence environmental degradation.

3.2 Variable Definitions

The variables used in the empirical analysis are summarized in Table 1. CO_2 emissions per capita represent the level of environmental degradation, while GDP per capita captures the level of economic development. The squared GDP per capita variable is included to identify whether the growth, emissions relationship follows an inverted U-shaped pattern. Energy consumption reflects the scale of energy demand, renewable energy share represents the transition toward cleaner energy sources, FDI captures international capital inflows, and trade openness reflects the degree of integration into global markets.

Table 1. Variable Definitions and Data Sources

Variable	Description	Measurement	Source
CO2pc	CO_2 emissions per capita	Metric tons per capita	WDI / GCB
GDPpc	GDP per capita	Constant 2015 US$	WDI
$GDPpc^2$	Squared GDP per capita	$(\text{Constant 2015 US\$})^2$	Computed
EC	Energy consumption	Kg oil equiv. per capita	WDI / IEA
RE	Renewable energy share	% of total final energy	WDI / IEA
FDI	Foreign direct investment	Net inflows (% of GDP)	WDI
TO	Trade openness	(Exports+Imports)/GDP × 100	WDI

To reduce heterogeneity and improve coefficient interpretation, CO_2 emissions, GDP per capita, and energy consumption are transformed into natural logarithms. The renewable energy share, FDI, and trade openness variables are retained in percentage form because they are already expressed as relative indicators.

3.3 Econometric Model Specification

The empirical model is constructed within the Environmental Kuznets Curve framework, which assumes a nonlinear relationship between income and environmental degradation. The EKC hypothesis predicts that CO_2 emissions increase at the early stage of economic development but decline after a certain income threshold is reached. To test this hypothesis, CO_2 emissions per capita are specified as a function of GDP per capita, squared GDP per capita, and a set of control variables.

The baseline panel regression model is specified as follows:

$$\ln(CO2pc_{it}) = \alpha_i + \beta_1 \ln(GDPpc_{it}) + \beta_2 [\ln(GDPpc_{it})]^2 + \beta_3 \ln(EC_{it}) + \beta_4 RE_{it} + \beta_5 FDI_{it} + \beta_6 TO_{it} + \varepsilon_{it} \tag{1}$$

where i denotes country, t denotes year, α_i captures unobserved country-specific effects, and ε_{it} represents the idiosyncratic error term. The coefficients β_1 and β_2 are the main parameters used to evaluate the EKC hypothesis. Evidence of an inverted U-shaped relationship is obtained when $\beta_1 > 0$ and $\beta_2 < 0$, indicating that emissions initially rise with income but eventually decline after reaching a turning point.

The income turning point is calculated using the following equation:

$$GDPpc^* = \exp\left(\frac{-\beta_1}{2\beta_2}\right) \tag{2}$$

This transformation is required because GDP per capita is expressed in logarithmic form. The resulting turning point represents the income level at which CO_2 emissions begin to decrease, assuming the EKC condition is statistically supported.

3.4 Estimation Strategy

The estimation strategy is designed to provide both baseline and robustness evidence regarding the relationship between economic growth and environmental degradation. The empirical analysis proceeds in four stages.

First, Pooled Ordinary Least Squares is estimated as an initial benchmark. Although this model provides a simple baseline, it does not account for unobserved country-specific heterogeneity. Second, the Fixed Effects model is applied to control for time-invariant characteristics across countries, such as geography, institutional background, historical development patterns, and long-term energy structures. Third, the Random Effects model is estimated under the assumption that unobserved country-specific effects are not correlated with the explanatory variables. The Hausman specification test is then used to determine whether the Fixed Effects or Random Effects estimator is more appropriate (Hausman, 1978).

Fourth, System Generalized Method of Moments is employed to address potential endogeneity and dynamic persistence in CO_2 emissions. Endogeneity may arise because economic growth can increase emissions, while environmental degradation and energy constraints may also affect economic performance. In addition, CO_2 emissions tend to be persistent over time because energy infrastructure, industrial structure, and consumption patterns do not change immediately. System GMM is appropriate for this context because it allows the inclusion of lagged dependent variables and uses internal instruments derived from lagged levels and lagged differences of the variables (Arellano & Bond, 1991), (Arellano & Bover, 1995), (Blundell & Bond, 1998).

The dynamic panel model is specified as follows:

$$\ln(CO2pc_{it}) = \gamma \ln(CO2pc_{i,t-1}) + \beta_1 \ln(GDPpc_{it}) + \beta_2[\ln(GDPpc_{it})]^2 + X'_{it}\delta + \alpha_i + \lambda_t + \varepsilon_{it} \quad (3)$$

where $\ln(CO2pc_{i,t-1})$is the lagged dependent variable, γmeasures emissions persistence, X'_{it}represents the vector of control variables, $\delta$is the corresponding coefficient vector, $\alpha_i$denotes country-specific effects, and $\lambda_t$captures time-specific effects.

The validity of the System GMM estimation is assessed using standard post-estimation tests. The Hansen or Sargan test is used to evaluate the validity of over-identifying restrictions, while the Arellano, Bond serial correlation test is applied to examine whether second-order autocorrelation is absent in the differenced residuals. The absence of AR(2) correlation and the validity of instruments are necessary conditions for reliable System GMM estimates. When two-step System GMM is applied, Windmeijer-corrected standard errors are recommended to reduce finite-sample bias in the estimated standard errors (Windmeijer, 2005), (Roodman, 2009)

3.5 Panel Diagnostic Tests

Several diagnostic tests are conducted before the main estimation to ensure that the panel model is statistically appropriate. First, panel unit root tests are applied to examine the stationarity properties of the variables. The (Levin et al., 2002), (Im et al., 2003), tests are used to determine whether the variables are stationary at level or after first differencing. This step is important because non-stationary variables may produce biased or spurious regression results if not properly handled.

Second, panel cointegration tests are conducted to evaluate whether a long-run equilibrium relationship exists among CO_2 emissions, GDP per capita, energy consumption, renewable energy, FDI, and trade openness. The Pedroni and Kao tests are used for this purpose. Evidence of cointegration would support the existence of a long-run relationship among the variables, which is consistent with the theoretical foundation of the EKC framework.

Third, multicollinearity is examined using the Variance Inflation Factor. This test is necessary because the inclusion of GDP per capita and its squared term may increase correlation among regressors. Although some correlation is expected in quadratic EKC models, excessive multicollinearity may reduce the precision of coefficient estimates.

Fourth, cross-sectional dependence is assessed using the Pesaran CD test. This test is relevant because developing countries may be affected by common shocks such as global energy price fluctuations, international financial crises, climate agreements, or trade disruptions. Ignoring cross-sectional dependence may lead to biased inference in panel data estimation.

Overall, the diagnostic tests are used to ensure that the empirical specification is consistent with the statistical properties of the data and that the estimated results provide reliable evidence on the relationship between economic growth and environmental degradation.

3.6 Regional Emissions Trend Analysis

Before presenting the regression results, the article also provides a descriptive regional trend analysis of CO_2 emissions per capita from 2000 to 2022. This analysis is intended to illustrate differences in emission trajectories across the five developing regions included in the sample.

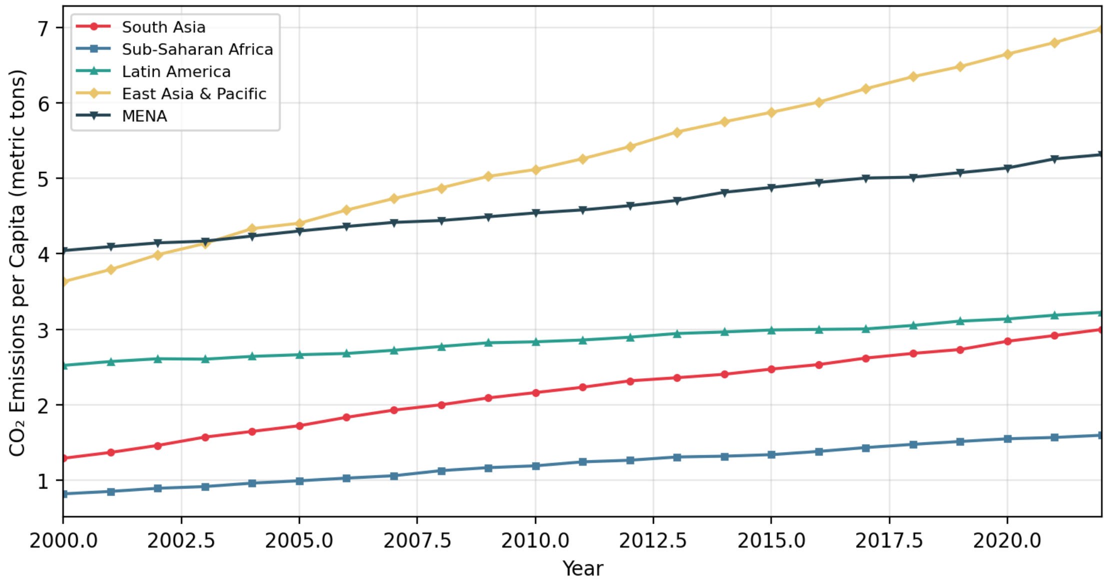

Figure 1. CO_2 Emissions per Capita Trends by Region, 2000-2022

Figure 1 illustrates regional variation in CO_2 emissions per capita. East Asia and the Pacific shows a relatively steep upward trend, reflecting rapid industrialization, urban expansion, and rising energy demand in several emerging economies. The Middle East and North Africa records higher average emissions levels, largely associated with fossil fuel dependence and energy-intensive production structures. Sub-Saharan Africa exhibits the lowest emissions per capita, but its gradual increase suggests an early stage of energy-intensive development. Latin America and the Caribbean, as well as South Asia, show more moderate trajectories, although both regions continue to face challenges in balancing economic growth, energy access, and environmental sustainability.

This regional pattern provides preliminary descriptive evidence that the growth, emissions relationship differs across developing regions. Therefore, the subsequent econometric analysis is necessary to determine whether the EKC hypothesis holds after controlling for energy consumption, renewable energy, FDI, trade openness, and unobserved country-specific characteristics.

4. RESULTS AND DISCUSSION

4.1 Descriptive Statistics

Descriptive statistics are presented to provide an initial overview of the distribution and variation of the variables used in the empirical analysis. The dataset consists of 1,495 country-year observations, representing 65 developing countries over the period 2000–2022. The descriptive results indicate substantial heterogeneity across countries in terms of carbon emissions, income level, energy consumption, renewable energy use, foreign direct investment, and trade openness.

Table 2. Descriptive Statistics of Research Variables

Variable	Mean	Std. Dev.	Min	Max	Obs.
CO2pc	3.247	3.518	0.042	16.854	1,495
GDPpc	4,892.3	3,714.6	312.8	14,856.2	1,495
$GDPpc^2$ ($\times 10^6$)	37.68	52.14	0.098	220.71	1,495
EC	1,287.4	1,042.8	98.6	5,432.1	1,495
RE (%)	32.48	24.16	0.12	94.37	1,495
FDI (%GDP)	3.87	5.24	-8.42	42.63	1,495
TO (%GDP)	72.34	34.87	15.28	210.42	1,495

Table 2 indicates that the average CO_2 emissions per capita among the sampled developing countries are 3.247 metric tons, with a standard deviation of 3.518. The relatively high standard deviation compared with the mean suggests substantial variation in emission intensity across countries. This pattern reflects differences in production structures, fossil fuel dependence, industrial capacity, and stages of economic development.

GDP per capita records an average value of US$4,892.3, with values ranging from US$312.8 to US$14,856.2. This broad range confirms that the sample includes countries at different development levels, from low-income economies to upper-middle-income developing economies. Such variation is relevant for examining the Environmental Kuznets Curve because the EKC hypothesis assumes that the relationship between income and environmental degradation may change as countries move from lower to higher income levels.

Energy consumption also shows considerable variation, with an average of 1,287.4 kg of oil equivalent per capita and a maximum value of 5,432.1. This indicates that energy demand differs substantially across the sampled countries. Renewable energy share has an average value of 32.48%, but the range from 0.12% to 94.37% shows that renewable energy adoption remains highly uneven. Some countries still rely heavily on conventional energy sources, while others have a much larger share of renewable energy in their energy mix.

FDI net inflows average 3.87% of GDP, although the maximum value of 42.63% suggests that some countries experience relatively high foreign investment inflows. Trade openness also varies widely, with an average of 72.34% of GDP and a maximum value of 210.42%. These descriptive patterns indicate that the sample provides sufficient variation to examine how income, energy structure, investment, and trade relate to CO_2 emissions in developing economies.

4.2 Panel Unit Root Tests

Before estimating the panel regression models, panel unit root tests were conducted to examine the stationarity properties of the variables. This procedure is required because non-stationary variables may lead to unreliable inference if their time-series properties are ignored. The results of the Levin–Lin–Chu, Im–Pesaran–Shin, ADF-Fisher, and PP-Fisher tests are reported in Table 3.

Table 3. Panel Unit Root Test Results

Variable	LLC	IPS	ADF-Fisher	PP-Fisher	Order	Decision
ln(CO2pc)	-1.842	-1.523	148.32	152.67	I(1)	1st diff
ln(GDPpc)	-1.214	-0.987	121.45	118.93	I(1)	1st diff
$[\ln(GDPpc)]^2$	-1.358	-1.102	132.18	129.74	I(1)	1st diff
ln(EC)	-2.134*	-1.892	156.42	161.28	I(1)	1st diff
RE	-3.842***	-3.214***	218.67***	224.31***	I(0)	Level
FDI	-4.126***	-3.897***	242.18***	238.94***	I(0)	Level
TO	-2.967**	-2.412**	187.63**	192.47**	I(0)/I(1)	Mixed

The results in Table 3 show that ln(CO2pc), ln(GDPpc), $[\ln(GDPpc)]^2$, and ln(EC) are not stationary at level but become stationary after first differencing. These variables are therefore classified as integrated of order one, I(1). This result is consistent with the nature of macroeconomic and environmental indicators, which tend to evolve gradually over time and may follow long-term development paths.

In contrast, renewable energy share and FDI are stationary at level, indicating that both variables are integrated of order zero, I(0). Trade openness shows mixed results across the tests, suggesting that its stationarity property is not uniform. The presence of both I(0) and I(1) variables indicates that the dataset contains mixed integration characteristics.

These results support the need for an estimation strategy that is sensitive to both cross-country heterogeneity and dynamic relationships over time. The combination of static panel estimators and System GMM is therefore appropriate because the model examines not only contemporaneous associations but also potential persistence and endogeneity in the relationship between economic growth and CO_2 emissions.

The preliminary pattern of the relationship between income and emissions is presented in Figure 2. This figure provides a visual indication of whether the Environmental Kuznets Curve pattern appears in the pooled sample before the regression model is estimated.

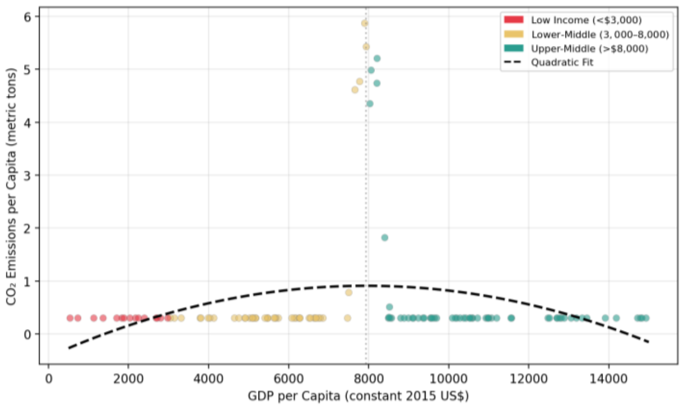

Figure 2. Environmental Kuznets Curve: GDP per Capita vs CO_2 Emissions in Developing Countries

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Figure 2 shows a nonlinear relationship between GDP per capita and CO_2 emissions per capita. At lower levels of income, CO_2 emissions tend to increase as GDP per capita rises. This pattern reflects the early development stage, where economic expansion is commonly accompanied by higher energy consumption, industrial activity, and infrastructure development. After a certain income level, the fitted curve begins to flatten and decline, suggesting the presence of an inverted U-shaped relationship.

This visual evidence is consistent with the Environmental Kuznets Curve hypothesis. However, the figure should be interpreted as preliminary evidence only. It does not account for other variables that may influence CO_2 emissions, such as energy consumption, renewable energy share, FDI, and trade openness. Therefore, the EKC relationship must be assessed more rigorously through the panel regression results.

The structure of the empirical relationship among the variables is summarized in Figure 3. This framework clarifies the expected role of each explanatory variable in determining CO_2 emissions per capita.

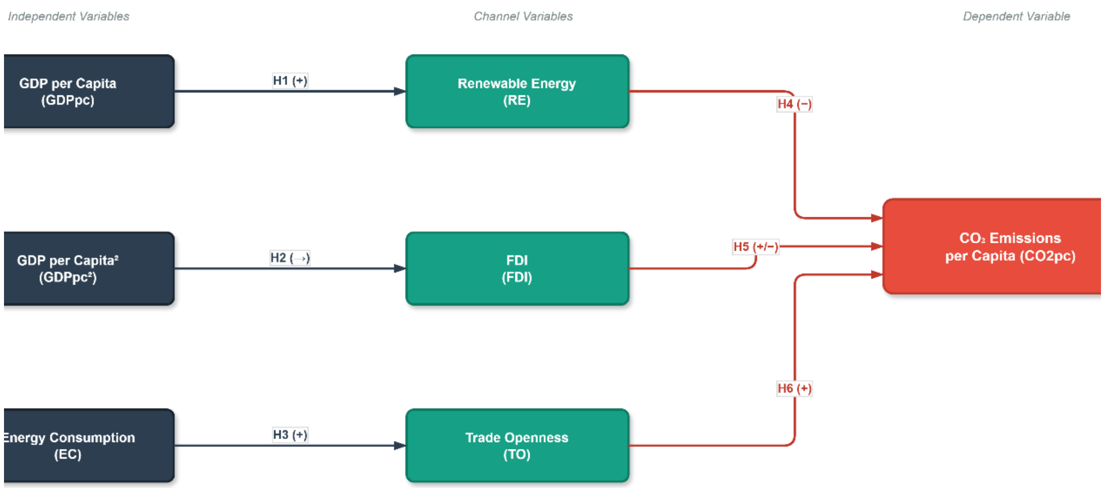

Figure 3. Conceptual Framework of the Research Model

Figure 3 illustrates the conceptual framework of the research model. GDP per capita is expected to increase CO_2 emissions at the early stage of development, while squared GDP per capita is expected to reduce emissions after a certain income threshold is reached. Together, these two variables represent the EKC mechanism.

Energy consumption is expected to have a positive effect on CO_2 emissions because higher energy demand often increases fossil fuel use. Renewable energy share is expected to reduce emissions by improving the composition of the energy mix. FDI has an ambiguous expected effect because it may either increase emissions through pollution-intensive investment or reduce emissions through cleaner technology transfer. Trade openness is expected to increase emissions when trade expansion is driven by production growth, resource extraction, or energy-intensive exports.

Thus, Figure 3 provides the theoretical basis for estimating the determinants of CO_2 emissions in the panel regression model.

4.3 Panel Regression Results

The main empirical results are presented in Table 4. Four estimation approaches are used: Pooled OLS, Fixed Effects, Random Effects, and System GMM. Pooled OLS provides the baseline estimate, Fixed Effects controls for unobserved country-specific heterogeneity, Random Effects offers an alternative specification under different assumptions about unobserved effects, and System GMM addresses potential endogeneity and dynamic persistence in emissions.

Table 4. Panel Regression Estimation Results

Variable	Pooled OLS	Fixed Effects	Random Effects	System GMM
ln(GDPpc)	0.498*** (0.067)	0.542*** (0.054)	0.498*** (0.058)	0.612*** (0.083)
[ln(GDPpc)]²	-0.028*** (0.008)	-0.031*** (0.006)	-0.028*** (0.007)	-0.035*** (0.009)
ln(EC)	0.401*** (0.042)	0.387*** (0.038)	0.401*** (0.039)	0.358*** (0.051)
RE	-0.195*** (0.031)	-0.218*** (0.027)	-0.195*** (0.029)	-0.241*** (0.038)
FDI	0.102 (0.068)	0.089 (0.061)	0.102 (0.064)	0.074 (0.078)
TO	0.131*** (0.038)	0.124*** (0.034)	0.131*** (0.036)	0.108** (0.044)
L.ln(CO2pc)	—	—	—	0.274*** (0.062)
Constant	-2.847*** (0.412)	-3.124*** (0.387)	-2.847*** (0.398)	-3.518*** (0.492)
R^2 (within)	0.41	0.68	0.62	—
R^2 (overall)	0.55	0.72	0.69	—
Hausman Test	—	—	χ^2=47.82***	—
Sargan Test	—	—	—	p = 0.342
AR(2) Test	—	—	—	p = 0.518
Observations	1,495	1,495	1,495	1,430
Countries	65	65	65	65

Table 4 provides consistent evidence in support of the Environmental Kuznets Curve hypothesis. In all estimation models, ln(GDPpc) has a positive and statistically significant coefficient, while [ln(GDPpc)]² has a negative and statistically significant coefficient. This coefficient pattern indicates that CO_2 emissions increase during the early stage of income growth but decrease after a higher level of income is reached.

The Fixed Effects model is selected as the preferred static panel model because the Hausman test is statistically significant. This result indicates that unobserved country-specific effects are correlated with the explanatory variables. In the Fixed Effects model, the coefficient of ln(GDPpc) is 0.542, while the coefficient of [ln(GDPpc)]² is -0.031. Based on these estimates, the EKC turning point is calculated as follows:

$$GDPpc^* = exp\left(\frac{-0.542}{2(-0.031)}\right) = exp(8.742) \approx US\$6{,}270 \quad (4)$$

The estimated turning point implies that CO_2 emissions begin to decline when GDP per capita reaches approximately US$6,270. This result suggests that many developing countries may still be positioned on the upward-sloping segment of the EKC, where income growth remains associated with higher emissions. Therefore, the finding should not be interpreted as evidence that economic growth automatically improves environmental quality. Instead, income growth must be supported by cleaner energy systems and stronger environmental governance to reduce emissions.

Energy consumption has a positive and statistically significant coefficient across all estimation models. In the Fixed Effects model, the coefficient of ln(EC) is 0.387, indicating that a 1% increase in energy consumption per capita is associated with an approximately 0.387% increase in CO_2 emissions per capita, holding other variables constant. This confirms that energy use is a major channel through which economic activity contributes to environmental degradation.

Renewable energy share has a negative and statistically significant coefficient in all specifications. The Fixed Effects coefficient of -0.218 indicates that a higher renewable energy share is associated with lower CO_2 emissions. This finding emphasizes the importance of energy composition in reducing environmental pressure. In other words, the environmental impact of growth depends not only on the level of energy consumption but also on whether the energy mix shifts toward cleaner sources.

FDI has a positive but statistically insignificant coefficient across all models. This result indicates that foreign direct investment does not have a clear aggregate effect on CO_2 emissions in the sample. The insignificant result suggests that the environmental effect of FDI may depend on sectoral allocation, regulatory quality, and the technological characteristics of foreign investment. Therefore, the full-sample result does not provide sufficient evidence to support either the pollution haven or pollution halo argument.

Trade openness has a positive and statistically significant coefficient. In the Fixed Effects model, the coefficient of TO is 0.124, indicating that greater trade openness is associated with higher CO_2 emissions. This finding suggests that trade expansion may increase environmental pressure when it is linked to production growth, energy-intensive industries, or resource-based exports.

The System GMM results support the robustness of the main findings. The lagged dependent variable is positive and statistically significant, indicating persistence in CO_2 emissions over time. The Sargan test p-value of 0.342 suggests that the instruments used in the model are valid, while the AR(2) test p-value of 0.518 indicates no evidence of second-order serial correlation. These diagnostic results support the reliability of the dynamic panel estimates.

The coefficient patterns and comparative model performance are further illustrated in Figure 4.

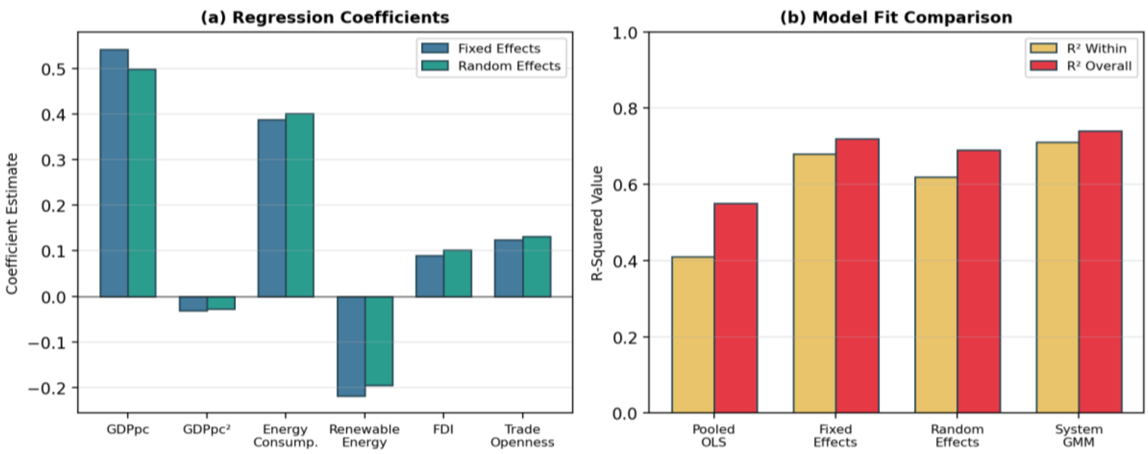

Figure 4. Estimation Results: Regression Coefficients and Model Fit Comparison

Figure 4 confirms that the estimated coefficient signs are stable across the panel models. GDP per capita consistently has a positive coefficient, while squared GDP per capita consistently has a negative coefficient. This visual comparison reinforces the regression evidence for the EKC hypothesis. Energy consumption maintains a positive association with CO_2 emissions, whereas renewable energy share consistently shows a negative association.

The model fit comparison also indicates that the Fixed Effects model provides stronger explanatory performance than the Pooled OLS and Random Effects specifications. However, the

System GMM model should be evaluated primarily through diagnostic tests rather than R^2 values. In this case, the Sargan and AR(2) test results indicate that the dynamic specification is acceptable.

4.4 Robustness Checks

Robustness checks were conducted to assess whether the main findings remain stable across regional sub-samples and a more recent time period. This step is important because developing regions differ in terms of industrial structure, energy dependence, income level, and policy capacity. The robustness results are presented in Table 5.

Table 5. Robustness Checks: Sub-Sample and Alternative Specifications

Variable	Sub-Saharan Africa	South & East Asia	Latin America	MENA	Post-2010
ln(GDPpc)	0.624***	0.512***	0.478***	0.398**	0.567***
$[\ln(GDPpc)]^2$	-0.038***	-0.029***	-0.025**	-0.018*	-0.033***
ln(EC)	0.412***	0.374***	0.356***	0.298***	0.392***
RE	-0.187***	-0.234***	-0.242***	-0.156**	-0.251***
FDI	0.124*	0.067	0.045	0.198**	0.082
TO	0.156***	0.118***	0.098**	0.142**	0.134***
EKC Valid?	Yes	Yes	Yes	Weak	Yes
Turning Point	$5,124	$9,218	$12,436	$15,842	$7,856
Obs.	437	368	345	345	845

The results in Table 5 show that the EKC pattern is generally supported across most sub-samples, although the strength of the relationship differs by region. Sub-Saharan Africa has a positive and significant coefficient for ln(GDPpc) and a negative and significant coefficient for $[\ln(GDPpc)]^2$, with an estimated turning point of US$5,124. This suggests that emissions in the region may respond strongly to income changes during the early development stage.

South and East Asia also show evidence of an inverted U-shaped relationship, with a turning point of US$9,218. This indicates that emissions may continue to rise until countries reach a relatively higher income level. Latin America records a higher turning point of US$12,436, suggesting that the income threshold for emission reduction is not uniform across regions.

The MENA region shows weaker evidence of the EKC pattern. Although the signs of the coefficients are consistent with the EKC hypothesis, the squared GDP coefficient is only weakly significant, and the estimated turning point is relatively high at US$15,842. This result suggests that fossil fuel dependence and energy-intensive economic structures may delay the decline in emissions in this region.

The post-2010 specification remains consistent with the full-sample results. GDP per capita has a positive coefficient, squared GDP per capita has a negative coefficient, energy consumption increases emissions, and renewable energy share reduces emissions. These findings indicate that the main empirical relationship remains stable in the more recent period.

The robustness checks therefore strengthen the main conclusion that the relationship between income growth and CO_2 emissions follows an inverted U-shaped pattern in developing countries, but the timing and strength of the turning point vary across regional contexts.

4.5 Granger Causality Analysis

To complement the panel regression results, Granger causality tests were conducted to examine whether past values of one variable help predict another variable. This analysis is useful for identifying the temporal direction of association among GDP per capita, CO_2 emissions, energy consumption, renewable energy share, FDI, and trade openness. The results are presented in Table 6.

Table 6. Pairwise Granger Causality Test Results

Null Hypothesis	F-Statistic	p-Value	Decision
GDPpc does not Granger-cause CO2pc	8.427	0.001***	Reject
CO2pc does not Granger-cause GDPpc	3.214	0.042**	Reject
EC does not Granger-cause CO2pc	12.856	0.000***	Reject
CO2pc does not Granger-cause EC	2.187	0.114	Fail to Reject
RE does not Granger-cause CO2pc	6.742	0.001***	Reject
CO2pc does not Granger-cause RE	1.893	0.152	Fail to Reject
FDI does not Granger-cause CO2pc	1.542	0.215	Fail to Reject
TO does not Granger-cause CO2pc	4.318	0.014**	Reject

Table 6 indicates a bidirectional predictive relationship between GDP per capita and CO_2 emissions. The null hypothesis that GDPpc does not Granger-cause CO2pc is rejected, and the null hypothesis that CO2pc does not Granger-cause GDPpc is also rejected. This means that past values of GDP per capita help predict CO_2 emissions, while past values of CO_2 emissions also help predict GDP per capita. This finding supports the view that economic growth and environmental degradation are dynamically interrelated.

Energy consumption Granger-causes CO_2 emissions, while the reverse relationship is not statistically significant. This suggests that changes in energy consumption precede changes in emissions. Renewable energy share also Granger-causes CO_2 emissions, indicating that changes in the energy mix contain predictive information about future emissions. These findings are consistent with the regression results, where energy consumption increases emissions and renewable energy share reduces emissions.

Trade openness also Granger-causes CO_2 emissions, supporting the finding that greater trade integration is associated with higher emissions. In contrast, FDI does not show a statistically significant predictive relationship with CO_2 emissions. This result aligns with the insignificant FDI coefficient in the panel regression models.

The Granger causality results should be interpreted as evidence of predictive association rather than definitive structural causality. Nevertheless, they reinforce the dynamic nature of the relationship among economic growth, energy structure, trade openness, and environmental degradation.

The dynamic response of CO_2 emissions to shocks in GDP per capita and renewable energy share is further illustrated in Figure 5.

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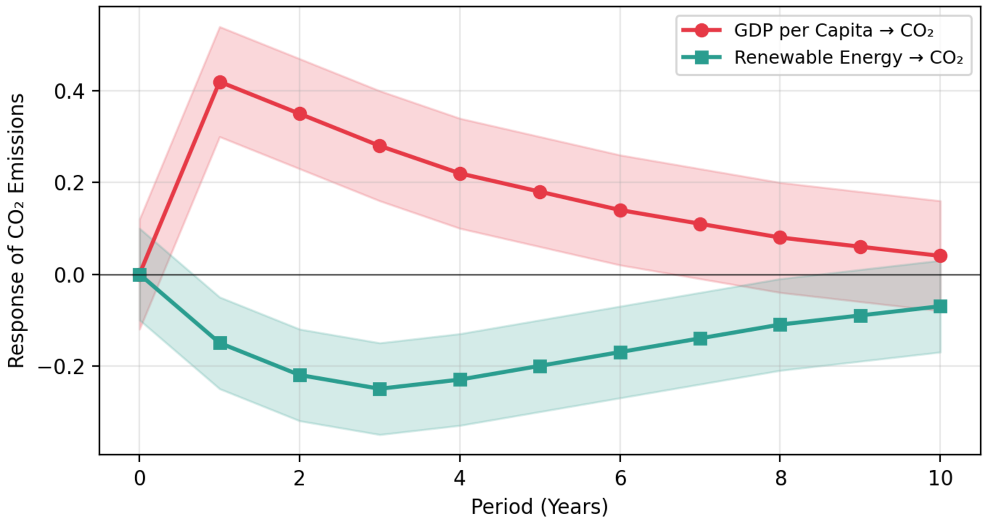

Figure 5. Impulse Response Functions: Response of CO_2 Emissions to GDP and Renewable Energy Shocks

Figure 5 presents the impulse response functions showing how CO_2 emissions respond to shocks in GDP per capita and renewable energy share. A positive shock to GDP per capita increases CO_2 emissions in the short run, with the response reaching its highest level in the second period before gradually declining. This pattern indicates that economic expansion can generate immediate environmental pressure, particularly when growth remains supported by energy-intensive activities.

In contrast, a positive shock to renewable energy share reduces CO_2 emissions over time. The effect becomes more visible after several periods, suggesting that renewable energy adoption may require an adjustment period before producing substantial emission-reducing effects. This delayed response is reasonable because renewable energy transitions depend on infrastructure investment, technology diffusion, and gradual substitution away from fossil fuels.

The impulse response analysis complements the regression results by showing that the effects of GDP and renewable energy are dynamic rather than purely contemporaneous. GDP growth tends to increase emissions in the short run, while renewable energy expansion contributes to emission reduction over a longer adjustment horizon.

4.6 Discussion

The empirical results provide consistent evidence that economic growth and environmental degradation in developing countries follow an inverted U-shaped relationship. The positive coefficient of GDP per capita and the negative coefficient of squared GDP per capita confirm the Environmental Kuznets Curve pattern across the main estimation models. This indicates that CO_2 emissions initially increase as income rises but begin to decline after a certain income threshold is reached.

The estimated turning point suggests that many developing countries may still be located on the upward-sloping segment of the EKC. This finding has an important implication: environmental improvement should not be expected to occur automatically through economic growth alone. If growth continues to rely on fossil fuel consumption and energy-intensive production, higher income may continue to generate higher emissions before the turning point is reached.

Energy consumption appears as one of the most robust determinants of CO_2 emissions. The positive and significant coefficient across all specifications indicates that rising energy demand directly contributes to environmental degradation. This result shows that the environmental consequences of growth are strongly mediated by the energy system. In developing countries, energy is essential for industrialization, infrastructure, transportation, and household welfare. However, when energy demand is supplied mainly by carbon-intensive sources, the expansion of energy consumption leads to higher CO_2 emissions.

Renewable energy share has a consistently negative and significant effect on CO_2 emissions. This finding shows that a cleaner energy mix can reduce the carbon intensity of economic development. The result also indicates that emission reduction does not depend solely on reducing energy consumption, but also on transforming the structure of energy supply. The impulse response analysis further suggests that the effect of renewable energy may occur gradually, emphasizing the importance of sustained investment in renewable energy infrastructure.

The effect of FDI is not statistically significant in the aggregate model. This implies that foreign investment does not have a uniform environmental effect across developing countries. FDI may increase emissions when it is directed toward extractive or pollution-intensive sectors, but it may reduce emissions when it brings cleaner technology and higher production standards. Therefore, the environmental effect of FDI depends on its quality, sectoral destination, and the regulatory framework of host countries.

Trade openness has a positive and significant relationship with CO_2 emissions. This result suggests that international market integration may increase environmental pressure when trade expansion is associated with energy-intensive production, resource-based exports, or manufacturing growth. The finding does not imply that trade is inherently harmful to the environment, but it indicates that trade liberalization without environmental safeguards may intensify emissions in developing countries.

Overall, the findings show that the EKC should be interpreted as a conditional development process rather than an automatic outcome of income growth. Economic growth can contribute to lower emissions only when supported by renewable energy expansion, cleaner technology adoption, stronger environmental governance, and more sustainable trade and investment policies. Therefore, developing countries should not follow a “grow first, clean later” strategy. Instead, green growth policies need to be integrated into the development process from an earlier stage.

5. CONCLUSION

5.1 Summary of Findings

This article provides empirical evidence on the relationship between economic growth and environmental degradation in developing countries by using a balanced panel dataset of 65 countries over the period 2000–2022. The analysis applies static panel estimators and System Generalized Method of Moments to examine whether the Environmental Kuznets Curve hypothesis holds after controlling for energy consumption, renewable energy share, foreign direct investment, and trade openness.

The findings confirm the presence of an inverted U-shaped relationship between GDP per capita and CO_2 emissions per capita. GDP per capita has a positive and statistically significant effect on CO_2 emissions, while the squared term of GDP per capita has a negative and statistically significant effect. Based on the Fixed Effects estimation, the estimated turning point is approximately US$6,270, indicating that emissions begin to decline only after countries reach a certain income threshold. This result suggests that many developing countries may still be located on the upward-sloping segment of the EKC, where economic expansion remains associated with rising emissions.

Energy consumption is found to be the strongest positive determinant of CO_2 emissions. This indicates that the environmental impact of economic growth is strongly mediated by the scale and structure of energy use. In contrast, renewable energy share has a significant negative effect on emissions, suggesting that cleaner energy composition can reduce environmental pressure and support the transition toward lower-carbon development.

The effect of FDI is positive but statistically insignificant in the aggregate model. This implies that foreign investment does not have a uniform environmental effect across developing countries. Its impact may depend on sectoral allocation, environmental regulation, and the technological characteristics of investment. Meanwhile, trade openness has a positive and statistically significant effect on emissions, indicating that international market integration may increase environmental pressure when trade expansion is associated with energy-intensive production or resource-based exports.

The System GMM results support the robustness of the main findings after accounting for endogeneity and emissions persistence. The significant lagged dependent variable confirms that CO_2 emissions are dynamic and tend to persist over time. Overall, the results show that economic growth alone is not sufficient to reduce environmental degradation. The transition toward cleaner energy systems, stronger environmental governance, and more sustainable trade and investment patterns is necessary to support green growth in developing countries.

5.2 Policy Implications

The findings provide several important policy implications. First, developing countries should not rely on the assumption that environmental quality will automatically improve after income increases. Although the EKC pattern is supported, the estimated turning point indicates that many countries may continue to experience rising emissions during the development process. Therefore, environmental policy should be integrated into economic development strategies from an earlier stage.

Second, energy policy should become a central component of emission reduction strategies. Since energy consumption has a strong positive effect on CO_2 emissions, governments need to improve energy efficiency, reduce dependence on fossil fuels, and accelerate the transition toward cleaner energy sources. Expanding renewable energy infrastructure, strengthening grid capacity, and supporting clean technology adoption are essential to reduce the carbon intensity of economic growth.

Third, the negative effect of renewable energy share highlights the importance of long-term investment in renewable energy. Policies that support solar, wind, hydro, biomass, and other clean energy sources can help developing countries reduce emissions while maintaining economic growth. Renewable energy transition should also be supported by fiscal incentives, regulatory certainty, and international climate finance.

Fourth, FDI policy should be directed not only toward increasing capital inflows but also toward improving the environmental quality of investment. Developing countries need to attract investment in cleaner industries, renewable energy, green infrastructure, and technology-intensive sectors. Environmental standards and investment screening mechanisms are necessary to prevent foreign capital from being concentrated in pollution-intensive activities.

Fifth, trade policy should incorporate environmental safeguards. Since trade openness is positively associated with CO_2 emissions, trade expansion should be accompanied by cleaner production standards, low-carbon industrial policies, and sustainability requirements. This is important to ensure that global market integration does not intensify environmental degradation in developing economies.

5.3 Limitations and Future Research

Despite its empirical contributions, this article has several limitations. First, the analysis uses aggregate national-level data, which may not fully capture sub-national, sectoral, or firm-level variations in the growth–emissions relationship. Environmental outcomes may differ across regions, industries, and production systems within the same country. Future research could use provincial, sectoral, or firm-level data to provide more detailed evidence.

Second, the sample consists of 65 developing countries, selected based on data availability. Although the sample provides broad regional coverage, it does not include all developing economies. Future studies could expand the country coverage when more complete data become available.

Third, the EKC framework provides a useful empirical structure, but it remains a reduced-form approach. It may not fully capture the institutional, technological, regulatory, and political factors that shape the relationship between economic growth and environmental quality. Future research could incorporate variables such as institutional quality, environmental regulation, green innovation, energy prices, and climate policy stringency.

Fourth, the period 2020–2022 includes the post-COVID-19 recovery phase, during which economic activity, energy demand, and emissions may have experienced temporary fluctuations. Future studies could extend the observation period to assess whether the estimated relationship remains stable after the recovery period.

Finally, future research may apply alternative methodological approaches, such as panel threshold models, nonlinear autoregressive distributed lag models, spatial panel models, or machine learning-based approaches, to explore nonlinearities, regional spillovers, and heterogeneous effects more comprehensively.

5.4 Concluding Statement

In conclusion, the findings demonstrate that the relationship between economic growth and CO_2 emissions in developing countries follows an inverted U-shaped pattern, but this relationship should not be interpreted as an automatic pathway toward environmental improvement. Economic growth can reduce emissions only when accompanied by renewable energy expansion, cleaner technology adoption, stronger environmental governance, and sustainable trade and investment policies. Therefore, developing countries need to pursue green growth strategies that align economic development with long-term environmental sustainability.

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