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The Impact of Innovation, Economic Growth, and Renewable Energy on CO_2 Emissions in Developing Countries

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ABSTRACT

This study examines the impact of economic growth, innovation, foreign trade, and renewable energy consumption on environmental sustainability in ten developing countries over the period 2000–2023. Based on panel data analysis, the research identifies strong cross-sectional dependence and structural heterogeneity among the countries. The results of the Westerlund and Edgerton (2007) cointegration test indicate the existence of a long-term relationship among the variables. According to the AMG estimator results, economic growth and renewable energy consumption exert a mitigating effect on carbon emissions. In contrast, the innovation variable increases emissions in the short run, suggesting that innovation activities have not yet fully shifted toward environmentally friendly technologies. The effect of foreign trade on carbon emissions, however, is found to be statistically insignificant. Overall, the findings suggest that achieving environmental sustainability in developing countries requires harmonizing economic growth with environmental policies. The study emphasizes the need to promote green innovation, increase investments in renewable energy, and support environmentally friendly production processes. In this context, it is recommended that environmental, energy, and innovation policies be implemented within an integrated development strategy.

Keywords: Economic Growth, Innovation, Renewable Energy, Developing Countries, Sustainable Development
JEL Classifications: Q42, O44, Q56

1. INTRODUCTION

In today's rapidly transforming global economy, the interaction among economic growth, innovation, and environmental sustainability lies at the core of development policies. Although traditional growth models have long sought to explain economic expansion through increases in production factors and capital accumulation, the rise of the knowledge-based economy has brought the view that innovation is the main driving force of growth to the forefront. At the same time, the environmental pressures generated by growing production and consumption activities have deepened the debate on the sustainability of economic growth. Climate change, energy security concerns, the depletion of natural resources, and disruptions in ecological balance have made the limits of growth-oriented development models increasingly apparent (Sethi et al., 2024; Khan and Rahmat, 2024).

Consequently, in the contemporary era, qualitative growth that prioritizes environmental sustainability has gained greater importance than mere quantitative expansion. For developing countries in particular, this reality necessitates the establishment of a complex balance between achieving economic development goals and fulfilling environmental commitments. In this context, the question of how innovation shapes the relationship between economic growth and environmental sustainability has drawn growing attention in both academic and policy circles in recent years. Indeed, Machado et al. (2024a), using data from 102 countries, identified a long-term relationship among economic growth, innovation, and environmental performance. Similarly, Utomo et al. (2024) demonstrated that investments in green technologies and economic diversification support sustainable development in developing economies.

While economic growth is generally measured by increases in per capita gross domestic product (GDP), innovation refers to the development of new products, processes, or technologies, the generation of knowledge, and improvements in productivity. Environmental sustainability, on the other hand, relates to the efficient use of natural resources, the reduction of carbon emissions, the preservation of biodiversity, and the minimization of environmental risks. A multidimensional and dynamic relationship exists among these three concepts. On one hand, innovation can reduce environmental burdens by improving energy efficiency in production processes through technological advancements; on the other, the expansion of production volumes can accelerate environmental degradation. This duality has brought to prominence the "Environmental Kuznets Curve" (EKC) hypothesis, frequently discussed in the literature. According to this hypothesis, economic growth increases environmental degradation up to a certain threshold, but as income levels rise, greater environmental awareness and technological capacity lead to a decline in degradation (Yessymkhanova et al., 2024a).

However, the EKC hypothesis does not hold universally across all countries and time periods. In many developing economies, where environmental protection policies are weak and innovation capacity is limited, the inverted-U relationship often fails to materialize. The fundamental challenge for developing countries is to accelerate growth and industrialization while simultaneously establishing innovative mechanisms to ensure environmental sustainability. Inadequate technological infrastructure, low R&D expenditures, limited human capital, production structures dependent on external inputs, and weak institutional frameworks often hinder the emergence of environmentally friendly forms of innovation. For instance, in many developing countries, economic growth remains heavily dependent on raw material exports and energy-intensive industries, thereby increasing carbon emissions and conflicting with sustainability objectives (Parmanova et al., 2025). Nonetheless, digitalization, renewable energy technologies, and green innovation practices are creating new opportunities for these countries (Syzdykova et al., 2021).

In recent years, policies promoting energy efficiency, waste management, environmentally friendly production systems, and clean technology investments have become more prevalent across developing countries, making the environmental benefits of innovation increasingly visible. Therefore, when guided by appropriate policy and institutional support mechanisms, innovation can act as a catalyst that simultaneously fosters economic growth and strengthens environmental sustainability.

Within this framework, holistic studies that evaluate the joint effects of innovation on economic growth and environmental sustainability in developing countries have gained importance. Such research can assist policymakers in designing economic development strategies that are compatible with environmental objectives. Sustainable development is now measured not only by economic growth rates but also by the environmental and social impacts of growth. The long-term prosperity of developing countries depends not only on expanding production volumes but also on enhancing energy efficiency, conserving natural resources, and mitigating environmental risks through innovation. Understanding the interaction among economic growth, innovation, and environmental sustainability is, therefore, a critical prerequisite—both academically and practically—for achieving sustainable development goals. This study aims to empirically analyze this relationship in the context of developing countries, examining the effects of innovation on growth and environmental sustainability from an integrated perspective and thereby contributing a scientific foundation for sustainable development policy formulation.

2. LITERATURE REVIEW

In the contemporary era, developing countries face a dual challenge: while striving to accelerate economic growth and development, they must also contend with global issues such as environmental degradation, resource depletion, and climate change. In this context, the role of innovation as a tool that simultaneously supports economic growth and mitigates environmental impacts has attracted increasing attention in the academic literature. Studies generally indicate that the relationship among economic growth, innovation, and environmental sustainability in developing countries is complex and multidimensional.

Research by Machado et al. (2024a; 2024b), Utomo et al. (2024), Adanma and Ogunbiyi (2024), and Aneja et al. (2024) demonstrates that innovation and green technologies play a balancing and positive role between economic growth and environmental sustainability. In contrast, studies such as Asif et al. (2024), Khan and Rahmat (2024), Muhammad et al. (2023), Fazal and Azam (2023), and Sulehri et al. (2024) suggest that while economic growth negatively affects the environment in the short term, innovation and effective governance can mitigate these adverse effects over time. Meanwhile, works by Koseoglu et al. (2022), Sethi et al. (2024), Özcan (2025), and Hunjra et al. (2024) emphasize that environmental improvements tend to emerge only after a certain income or technological threshold is surpassed, indicating that the Environmental Kuznets Curve (EKC) hypothesis may hold true for many developing countries.

Yessymkhanova et al. (2024a) confirmed the EKC hypothesis in BRIC countries, demonstrating that economic growth promotes environmental improvement once a specific income threshold is reached. In a related study, Yessymkhanova et al. (2024b) analyzed the determinants of energy consumption and highlighted the strong influence of innovation and growth on energy demand. Furthermore, Yessymkhanova et al. (2025) examined the relationship among current account balance, growth, and oil prices, drawing attention to the indirect effects of energy prices on environmental sustainability. Parmanova et al. (2025), analyzing the case of Kazakhstan, found that the interrelationship among energy consumption, economic growth, and population indicates that sustainable growth depends on energy efficiency.

In the context of the European Union, Azretbergenova et al. (2021) demonstrated that renewable energy production not only enhances environmental performance but also contributes to employment growth. Similarly, Syzdykova et al. (2020) confirmed a positive relationship between energy consumption and economic growth in Commonwealth of Independent States (CIS) countries, emphasizing the need to consider this relationship in environmental policy design. Expanding on this line of inquiry, Syzdykova et al. (2021) examined the relationship between renewable energy and economic growth in selected developing countries and concluded that renewable energy use supports economic growth while simultaneously strengthening environmental sustainability.

Machado et al. (2024a) demonstrate significant long-term relationships among economic growth, innovation, and environmental performance across 102 countries. By emphasizing that economic development influences both innovation and environmental sustainability, they highlight the need for integrated approaches to achieve sustainable futures in developing nations. Utomo et al. (2024) demonstrate that developing countries can achieve both economic growth and environmental sustainability by strengthening regulatory frameworks, investing in green technologies, and promoting economic diversification through sustainable tourism and organic agricultural trade that stimulate innovation while reducing resource pressure.

Asif et al. (2024) reveal that economic growth negatively affects environmental sustainability within BRICS economies, whereas technological innovation and financial development exert positive influences. They further emphasize that trade openness mediates these relationships, highlighting the complexity of achieving sustainable development in developing nations.

Machado et al. (2024b) emphasize that in developing countries, economic growth and innovation may initially harm environmental performance; however, as innovation intensifies, policies fostering sustainability-oriented innovation can lead to significant improvements in environmental outcomes.

Khan and Rahmat (2024) investigate how economic growth and innovation affect CO_2 emissions in developing economies, confirming the Environmental Kuznets Curve (EKC) hypothesis. Their findings indicate that innovation and energy consumption increase emissions, while political stability and anti-corruption measures can enhance environmental sustainability.

Muhammad et al. (2023) validate the EKC hypothesis, showing that while economic growth initially deteriorates environmental quality, it improves over time. They underscore the critical role of technological innovation in reducing ecological footprints in developing countries such as Thailand, whereas natural resources exhibit limited influence.

Fazal and Azam (2023) find that economic growth aggravates environmental degradation, while technological innovation and renewable energy consumption reduce CO_2 emissions. They stress that good governance amplifies the positive effects of innovation and renewable energy, thereby fostering environmental sustainability.

Koseoglu et al. (2022) demonstrate that although economic growth primarily contributes to environmental degradation, green innovation—particularly environmentally related technologies—can substantially mitigate ecological footprints. They emphasize that sustainable development can be achieved through strategic investments in green innovation.

Hunjra et al. (2024) show that economic growth in developing economies may lead to cleaner technologies consistent with the EKC hypothesis. Nonetheless, high growth rates, abundant natural resources, and substantial foreign direct investment can exacerbate environmental degradation, calling for context-specific sustainability strategies.

Khanna et al. (2025) indicate that in G20 countries, economic growth is closely linked to rising energy consumption, whereas innovation (measured through R&D and patents) is associated with reduced carbon emissions. They highlight the necessity of balancing growth with sustainability through advancements in clean technologies.

Adanma and Ogunbiyi (2024) stress the pivotal role of technological innovation in achieving sustainability goals in developing nations. They advocate for integrated policy frameworks that align economic growth with environmental sustainability and promote international cooperation to effectively address global environmental challenges.

Aneja et al. (2024) reveal that economic growth, clean energy, and green innovation significantly influence environmental sustainability in G20 countries. They argue that balancing economic expansion with sustainable practices is essential to mitigating environmental degradation, particularly in developing contexts.

Sethi et al. (2024) demonstrate that while green technology innovation and green finance may initially contribute to CO_2 emissions in developing countries, agricultural value addition and renewable energy use have mitigating effects. Their study highlights the complex interlinkages among economic growth, innovation, and environmental sustainability.

Özcan (2025) finds that technological advancement enhances economic efficiency in developing economies; however, environmental benefits emerge only after reaching an income threshold of approximately USD 14,900. The study underscores the need for innovation strategies aligned with green growth to ensure sustainability.

Anwarya (2022) notes that although economic growth in developing countries is associated with increased carbon emissions, investments in environmental protection and renewable energy can mitigate these effects. The study emphasizes the necessity of sustainable development practices to balance growth and ecological stability.

Sulehri et al. (2024) reveal that while innovation positively influences economic growth, the effect is statistically insignificant. They further argue that economic growth substantially contributes to environmental degradation, underscoring the complex interplay between innovation, growth, and ecological impact.

3. METHODOLOGY AND DATASET

In this study, the relationship between the economy and environmental pollution, which has been examined from various perspectives in the literature, will be analyzed in terms of the impact of innovation on CO_2 emissions. Additionally, the study will investigate the relationship among renewable energy consumption, trade openness, and CO_2 emissions. The analysis covers ten developing countries—Argentina, Azerbaijan, Belarus, Brazil, China, Colombia, Kazakhstan, Mexico, Russia, and Türkiye—for which data are available for the period 2000–2023. The empirical model developed for this study is structured as follows:

$$InCO2_{it} = \beta_0 + \beta_1 InGDPPC_{it} + \beta_2 InINOV_{it} + \beta_3 InTRADE_{it} + \beta_4 InREN_{it} + \vartheta_t$$

In the model, the logarithmically transformed variables are defined as follows: $\ln CO_2$ represents environmental pollution, measured as per capita CO_2 emissions (metric tons); lnGDPPC denotes economic growth, measured by per capita gross domestic product (GDP); lnINOV captures innovation, expressed as the ratio of research and development (R&D) expenditures to GDP; lnTRADE reflects trade openness, measured as the ratio of total exports and imports of goods and services to GDP; and lnREN represents renewable energy consumption, measured as the share of renewable energy in total final energy consumption. Finally, ϑ_i denotes the error term. The data used in this study were obtained from the World Bank's World Development Indicators (WDI) database.

In this study, econometric methods based on panel data analysis were employed to examine the relationship between economic growth, innovation, and environmental sustainability in both the short and long run. To ensure the reliability and robustness of the results, the structural properties of the model were first tested. Accordingly, the homogeneity of the slope coefficients in the model was investigated using the Slope Homogeneity Test (Δ test) developed by Pesaran and Yamagata (2008). This test is an extended version of the classical Swamy (1970) test and determines whether the responses of cross-sectional units (such as countries, regions, or firms) to explanatory variables are identical (homogeneous) or differ across units (heterogeneous). The null hypothesis of the test is formulated as H_0: $\beta_I = \beta$ indicating slope homogeneity. The test statistic is expressed as:

$$\Delta = \sqrt{N0}\,\frac{(\tilde{S} - k)}{\sqrt{2k}}$$

where $\tilde{S}$ denotes the Swamy test statistic, k is the number of explanatory variables, and N represents the number of cross-sectional units. A statistically significant Δ value suggests that the coefficients are heterogeneous, implying structural differences across units. Consequently, methods that account for heterogeneity should be preferred in the analysis.

Another crucial assumption in panel data analysis is cross-sectional independence. Violation of this assumption may lead to biased and inconsistent estimates. To test for cross-sectional dependence among units, the Lagrange Multiplier (LM) test developed by Breusch and Pagan (1980) was first employed. This test measures the degree of correlation among the residuals across units and is calculated as:

$$LM = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T\hat{p}_{ij}^2$$

where $\hat{p}_{ij}$ denotes the pairwise correlation of residuals and T represents the time dimension. However, as the LM test can become overly sensitive in large samples, the Cross-Section Dependence (CD) test proposed by Pesaran (2004) was also applied. The CD test evaluates the average correlation among cross-sections and is computed as:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i<j} \hat{p}_{ij}$$

A significant CD statistic indicates the presence of cross-sectional dependence. Additionally, the bias-adjusted LMadj test developed by Pesaran et al. (2008) was utilized to obtain more reliable results when both N and T are large. This version corrects the mean and variance of the classical LM statistic, thereby reducing the test's sensitivity in large samples.

The stationarity properties of the variables were tested using the Hadri–Kurozumi (2012) second-generation unit root test, which accounts for cross-sectional dependence. This test is an improved version of the Hadri (2000) test, incorporating both homogenous and heterogeneous error structures. The null hypothesis is defined as H_0: Series are stationary. Thus, a significant test statistic indicates the presence of a unit root, meaning the series is non-stationary.

To determine the existence of a long-run equilibrium relationship among the variables, the LM cointegration test developed by Westerlund and Edgerton (2007) was applied. This test investigates whether the panel exhibits a common cointegration relationship, taking into account cross-sectional dependence and dynamic structures. The null hypothesis H_0: No cointegration implies the absence of a long-run equilibrium relationship; its rejection indicates the presence of cointegration among the series.

Finally, to estimate the long-run coefficients between the variables, the Augmented Mean Group (AMG) estimator developed by Eberhardt and Teal (2010) and Bond and Eberhardt (2013) was employed. The AMG estimator considers both heterogeneity and cross-sectional dependence by estimating individual regressions for each unit and then averaging the coefficients. Moreover, it incorporates common dynamic processes into the model, controlling for unobserved common factors that may affect all units simultaneously. This makes AMG particularly suitable for panels consisting of developing countries, where heterogeneity and interdependence are prevalent.

4. ANALYSIS FINDINGS

Before conducting unit root and cointegration analyses, cross-sectional dependence among the series was tested. The results of the cross-sectional dependence test for the variables included in the constructed model are presented in Table 1.

An examination of the results presented in Table 1 reveals that a substantial degree of cross-sectional dependence exists across all variables. The results of the Breusch–Pagan (1980) LM, Pesaran (2004) CDLM and CD tests, as well as the LMadj test developed by Pesaran et al. (2008), collectively indicate that the variables are not independent from one another. Specifically, for the variables $LNCO_2$, LNGDPPC, LNINOV, LNTRADE, and LNREN, the LM and CDLM test statistics are significant at the 1% level, demonstrating a strong cross-sectional dependence among the countries in the panel.

On the other hand, the Pesaran (2004) CD test yields significant results at the 5% level for certain variables (e.g., $LNCO_2$, LNTRADE, and LNREN), suggesting that cross-sectional dependence is relatively weaker for some variables but should still be considered across the entire panel. According to the LMadj (Pesaran et al., 2008) test, significant results are also observed for LNGDPPC, LNINOV, and LNREN, which are consistent with the previous findings.

Therefore, the results indicate a high degree of interdependence among developing countries in terms of economic growth, innovation, trade openness, renewable energy use, and carbon emissions, implying that these economies are affected by similar external shocks. Methodologically, this finding necessitates the use of second-generation panel unit root and cointegration tests to account for cross-sectional dependence.

The results of the Pesaran and Yamagata (2008) homogeneity test presented in Table 2 assess whether the parameters among the countries included in the panel are homogeneous. According to the findings, both the Delta Tilde (10.201) and Delta Tilde_adj (10.896) statistics are statistically significant at the 1% significance level (P = 0.000). This indicates that the null hypothesis of "homogeneous slope coefficients" is rejected.

Therefore, it is concluded that the effects of the variables in the model are not homogeneous across the countries in the panel. In other words, the relationships between economic growth, innovation, trade openness, renewable energy consumption, and carbon emissions vary from country to country. Since each country possesses distinct structural characteristics, economic policies, and environmental dynamics, the interactions among these variables are heterogeneous at the national level.

In panel data analyses, the selection of an appropriate unit root test depends on the existence of cross-sectional dependence. As shown in Table 1, the results indicate the presence of cross-sectional dependence among the series; therefore, the second-generation unit root test—specifically, the Hadri–Kurozumi (2012) panel unit root test—has been applied. The results are presented in Table 3.

The Hadri–Kurozumi (2012) panel unit root test results presented in Table 3 examine the stationarity properties of the series. In this test, the null hypothesis states that the series are stationary (i.e., they do not contain a unit root). Therefore, statistically insignificant P-values indicate that the series are non-stationary, meaning they contain a unit root. According to the results reported in the table, the probability values of both Z_A^{SPC} and Z_A^{LA} statistics for all variables are >0.05. This finding suggests that the null hypothesis of stationarity cannot be rejected, implying that the variables are not stationary at their levels (i.e., they contain a unit root). In other words, the environmental variable (carbon emissions), economic growth (GDP per capita), innovation, trade openness, and renewable energy consumption series are all non-stationary in their levels.

This result indicates that the series exhibit random movements over time and do not maintain a long-term equilibrium relationship in their level form. Based on these findings, it is methodologically necessary to difference the series once to achieve stationarity and then test for the existence of a cointegration relationship. The cointegration relationship among the variables is analyzed using the Westerlund and Edgerton (2007) Panel LM Bootstrap Cointegration Test, as shown in Table 4.

According to Table 4, since the bootstrap P-value (0.979) is >0.05, the null hypothesis cannot be rejected. This indicates the existence of a long-term cointegration relationship among the variables. In other words, economic growth, innovation, trade, renewable energy, and carbon emissions move together in the long run.

The AMG (Augmented Mean Group) estimator results presented in Table 5 reveal the effects of economic growth, innovation, trade openness, and renewable energy consumption on carbon emissions, both at the overall panel level and across individual

Table 1: Cross-sectional dependence test results by variable

Variables	LM (Breusch and Pagan 1980)		CDLM (Pesaran, 2004)		CD (Pesaran, 2004)		LMadj (Pesaran et al., 2008)	
	Statistic	Probability	Statistic	Probability	Statistic	Probability	Statistic	Probability
$LNCO_2$	112.139*	0.000	2.976*	0.000	−1.682*	0.027	0.208	0.697
LNGDPPC	143.297*	0.000	6.029*	0.000	−1.497**	0.059	6.386*	0.000
LNINOV	182.306*	0.000	8.040*	0.000	−2.193*	0.018	3.582*	0.000
LNTRADE	150.507*	0.000	5.399*	0.000	−2.013*	0.030	0.273	0.816
LNREN	122.904*	0.000	3.604*	0.000	−1.574*	0.038	2.301*	0.023

*, **Indicate significance levels of 1% and 5%, respectively

countries. These findings are highly significant as they illustrate how environmental sustainability in developing countries is shaped by economic and technological dynamics.

At the panel level, the coefficient for economic growth (LNGDPPC) is –0.053 and significant at the 1% level. This indicates that economic growth generally exerts a reducing effect on carbon emissions, suggesting that the growth process in the examined countries has become more environmentally sustainable. In other words, the expansion of economic activity in these nations reflects characteristics of "green growth."

The innovation variable (LNINOV) has a coefficient of 0.068, significant at the 5% level. This implies that innovation may increase emissions in the short term, possibly because R&D and innovation activities in developing countries are often concentrated in industrial sectors that consume large amounts of energy. However, in the long term, as environmentally friendly technologies become more widespread, the impact of innovation on emissions is expected to turn negative.

Table 2: Results Of The Pesaran and Yamagata (2008) Homogeneity test

Tests	Test statistic	Probability value
Delta Tilde	10.201*	0.000
Delta Tildeadj	10.896*	0.000

*Indicates significance at the 1% level

Table 3: Hadri–Kurozumi (2012) Panel Unit Root Test Results

Variables	Z_A^{SPC}	Z_A^{LA}
$LNCO_2$	−1.567	0.089
	[0.876]	[0.390]
LNGDPPC	−0.446	−0.206
	[0.267]	[0.581]
LNINOV	−1.018	−0.524
	[0.806]	[0.683]
LNTRADE	−0.458	0.903
	[0.605]	[0.210]
LNREN	−0.604	−0.472
	[0.695]	[0.330]

The optimal lag length was determined using the Schwarz Information Criterion (SIC)

Table 4: Westerlund and Edgerton (2007) Panel LM Bootstrap Cointegration test results

Model 1	LM Statistic	Asymptotic P value	Bootstrap P value
LMN^T	2.806	0.001	0.979

The number of bootstrap replications is set to 1000. The test results are obtained using a model with constant and trend

The trade openness variable (LNTRADE) is found to be statistically insignificant, suggesting that the effect of trade on carbon emissions does not follow a uniform direction. In some countries, trade expansion increases emissions due to higher production, while in others it reduces emissions by facilitating the import of clean technologies.

The renewable energy variable (LNREN) has a coefficient of –0.018 and is significant at the 1% level, clearly indicating that renewable energy consumption plays a crucial role in reducing carbon emissions. This highlights the importance of energy transition policies for achieving environmental sustainability.

Country-level results reveal the following patterns:

- In Azerbaijan and Kazakhstan, both economic growth and renewable energy reduce emissions, while trade openness increases them—likely due to the export orientation of energy-intensive industries.
- In China, economic growth and renewable energy reduce CO_2 emissions, but innovation and trade openness increase them. This suggests that China's innovation-driven industrial expansion has not yet fully aligned with green transformation objectives.
- For Türkiye, both economic growth (–0.637) and renewable energy (–0.280) significantly reduce emissions, while the slightly positive effect of innovation indicates the need for greater integration of environmental goals into technology and R&D policies.
- In Brazil and Colombia, innovation exerts a positive (emission-increasing) effect, while Brazil's renewable energy use strongly reduces emissions (–0.756).
- In Mexico, both growth and renewable energy reduce emissions, while trade openness has a modest but negative effect on emissions.

Table 5: AMG estimator results

Model: $lnCO2_{it} = \beta_0 + \beta_1 lnGDPPC_{it} + \beta_2 lnINOV_{it} + \beta_3 lnTRADE_{it} + \beta_4 lnREN_{it} + \vartheta_t$								
Group	lnGDPPC		lnINOV		lnTRADE		lnREN	
	Coefficient	Probability	Coefficient	Probability	Coefficient	Probability	Coefficient	Probability
	−0.053*	0.000	0.068**	0.052	0.197	0.701	-0.018*	0.000
Country Results								
Argentina	−0.405*	0.000	0.049	0.420	−0.016	0.472	−0.201	0.207
Azerbaijan	−1.039*	0.000	−0.076	0.304	0.193**	0.012	−0.309*	0.000
Kazakhstan	−0.360*	0.000	−0.210**	0.017	0.307***	0.050	−0.196*	0.000
Belarus	−0.706*	0.000	0.079	0.308	−0.078	0.346	0.071	0.703
Brazil	−0.104	0.396	0.204**	0.019	0.006	0.109	−0.756*	0.000
China	−0.057*	0.000	0.218**	0.070	0.167*	0.000	−0.245*	0.000
Colombia	−0.719*	0.000	0.259**	0.049	−0.702	0.217	−0.059	0.243
Mexico	−0.685**	0.012	0.068	0.301	−0.176***	0.052	−0.234***	0.050
Russia	−0.798*	0.000	0.019	0.734	0.183	0.308	−0.020***	0.086
Türkiye	−0.637*	0.000	0.110***	0.068	−0.057	0.683	−0.280*	0.001

*,**, and ***Indicate significance at the 1%, 5%, and 10% levels, respectively

Overall, the AMG estimator results demonstrate that in developing countries, economic growth and renewable energy use support environmental sustainability, whereas innovation—in its current form—does not yet contribute sufficiently to emission reduction. Therefore, innovation policies in these countries should be aligned not only with economic efficiency but also with carbon mitigation and green technology development goals.

In conclusion, the findings emphasize the importance of integrating environmental, energy, and innovation policies. By increasing renewable energy investments and grounding innovation activities in environmentally friendly principles, developing countries can more effectively balance economic growth and environmental sustainability in the long run.

5. CONCLUSION

This study analyzes the impact of economic growth, innovation, foreign trade, and renewable energy use on carbon emissions in ten developing countries during the period 2000–2023. The primary objective is to identify the key factors influencing environmental sustainability within the process of economic development and to derive policy-relevant insights for decision-makers.

The analysis results reveal a high degree of cross-sectional dependence among the countries, indicating that environmental problems are shaped by shared global dynamics. The homogeneity test demonstrates that structural differences exist across countries, implying that the effects of the variables vary depending on each nation's economic structure. This finding suggests that environmental policies should be adapted to the specific characteristics of individual economies. The cointegration test results confirm the existence of a long-term relationship among economic growth, innovation, foreign trade, renewable energy use, and carbon emissions. This finding verifies that environmental sustainability is closely intertwined with economic and technological dynamics over the long run.

According to the AMG estimator results, economic growth and renewable energy use generally contribute to reducing carbon emissions, whereas innovation increases emissions in the short term. This suggests that innovation in developing countries is not yet sufficiently oriented toward environmentally friendly technologies and tends to occur predominantly in energy-intensive sectors. The effect of foreign trade on carbon emissions is found to be statistically insignificant, indicating that the environmental impact of trade varies depending on national policies, energy structures, and production patterns.

In conclusion, it is crucial to align economic growth with environmental objectives, increase investments in renewable energy, and integrate innovation policies with ecological goals. For developing countries, key policy recommendations include:

- Enhancing incentives for green technology investments that reduce carbon emissions;
- Redirecting R&D support toward environmentally friendly production and energy efficiency;
- Strengthening international financing and technology transfer for renewable energy infrastructure; and
- Developing trade policies based on carbon footprint considerations.

Within this framework, environmental sustainability can be achieved not solely through environmental policies but through a holistic development vision that places economic growth and innovation strategies at its core. For developing countries, long-term sustainable growth will only be attainable through the simultaneous advancement of green innovation, energy transition, and the low-carbon economy.

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