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Revisiting the Environmental Innovation and Carbon Emissions Nexus: Does Development Level Matter?

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Abstract **Original Research Article**

Environmental innovation has emerged as a critical policy instrument for achieving sustainable development and mitigating climate change. However, existing studies provide mixed evidence regarding its effectiveness in reducing carbon emissions and often overlook differences between developed and developing economies. This study examines the impact of environmental innovation on per capita CO_2 emissions across 61 countries from 2000 to 2021. Environmental innovation is measured using the stock of environment-related patents, while carbon emissions are measured as per capita CO_2 emissions. To address unobserved heterogeneity, cross-sectional dependence, and potential endogeneity, the analysis employs fixed-effects, Driscoll-Kraay, and fixed-effects instrumental variable (FE-IV) estimators. The results indicate that environmental innovation significantly reduces CO_2 emissions in the full sample. However, substantial heterogeneity exists across country groups. Environmental innovation exerts a strong and statistically significant emissions-reducing effect in developed economies, whereas its impact is insignificant in developing economies. The findings also provide evidence supporting the Environmental Kuznets Curve hypothesis, suggesting a nonlinear relationship between economic growth and environmental degradation. Furthermore, the instrumental-variable results confirm the robustness of the main findings after accounting for endogeneity. The study contributes to the environmental innovation literature by highlighting the importance of technological and institutional conditions in shaping environmental outcomes. The findings suggest that while environmental innovation is an effective climate mitigation tool in developed economies, developing countries require complementary investments in institutional capacity, technological infrastructure, and policy support to fully realise its environmental benefits. These results offer important implications for climate policy, innovation strategy, and international technology cooperation.

Keywords: Environmental Innovation; CO_2 Emissions; Environmental Kuznets Curve; Panel Data Analysis; Instrumental Variables (IV) Estimation

JEL Classification: Q55, Q54, O13, C33, C36.

INTRODUCTION

The unprecedented rise in global CO_2 emissions has emerged as one of the most pressing environmental and policy challenges of our time. As the dominant contributor to greenhouse gas (GHG) concentrations, CO_2 emissions increased by 0.8 to 1.5 per cent in 2022 (Energy Institute, 2023), underscoring the urgency of identifying effective mitigation strategies. The scale of the problem is further illustrated by stark cross-country disparities the United States and the Russian Federation record per capita GHG emissions of approximately 18 and 19 tonnes CO_2, respectively, nearly three times the global average of 6.6 tonnes, while least developed economies, including India and those in the African Union, contribute substantially lower aggregate emissions. These divergences reflect not only differences in industrial structure and energy systems but also in technological capacity and institutional development, factors central to understanding how environmental innovation translates into emissions reductions.

Against this backdrop, policymakers, particularly in emerging and transition economies, are increasingly recognising the role of technological advancement in simultaneously achieving economic growth and environmental sustainability (Balsalobre-Lorente *et al.,*2021; Ullah *et al.,*2021). Historically, high energy consumption has been closely tied to CO_2 emissions due to reliance on fossil fuels (Salahuddin *et al.,*2015). However, technological innovation encompassing renewable energy deployment, energy efficiency improvements, and carbon management strategies has demonstrated considerable potential to decouple growth from emissions. Evidence from OECD and BRICS economies suggests that accelerated innovation and the adoption of renewable energy are essential to achieving meaningful emissions reductions (Khan *et al.,*2022; Khattak *et al.,*2020).

A growing body of empirical literature supports this view, confirming that green innovation and R&D expenditure play a vital role in reducing CO_2 emissions. Aliani *et al.,*(2024) demonstrate that renewable energy and environment-related technology significantly reduced emissions in G7 countries between 2000 and 2019. Hordofa *et al.,*(2023) find that eco-innovation and green investment mitigated CO_2 emissions in China over the period 1990-2019. Ponce and Khan (2021) establish that renewable energy and energy efficiency jointly contribute to emissions reductions across nine developed economies, while Fethi and Rahuman (2019) confirm that eco-innovation exerts a significant long-run emissions-reducing effect in refined oil-exporting countries. Mensah *et al.,*(2018) similarly demonstrate that innovation plays a crucial mitigating role across 28 OECD countries from 1990 to 2014.

Despite this growing evidence, three important gaps remain in the existing literature. First, the majority of studies assume a homogeneous relationship between environmental innovation and carbon emissions across countries, overlooking the significant variation in technological readiness, institutional quality, and absorptive capacity that characterises different economies. Imposing a uniform effect across heterogeneous country contexts risks producing misleading estimates and obscuring the conditions under which innovation is most effective. Second, there is limited evidence on whether the environmental innovation-emissions nexus differs systematically across developed and developing economies. Given that these two groups differ considerably in their innovation infrastructure, regulatory frameworks, and energy systems, their responsiveness to environmental innovation is unlikely to be identical. Treating them as a homogeneous bloc may therefore conceal policy-relevant heterogeneity. Third, the potential endogeneity of environmental innovation has received insufficient attention in the literature. Countries with higher emissions may simultaneously invest more in green innovation as a regulatory or reputational response, introducing reverse causality that conventional panel estimators fail to adequately address, thereby raising concerns about the consistency and reliability of reported findings.

This study addresses these gaps by investigating the heterogeneous effects of environmental innovation on carbon emissions across countries. Employing a rigorous empirical framework that incorporates fixed-effects, Driscoll-Kraay, and instrumental variable (IV) estimators, the analysis explicitly accounts for cross-sectional dependence and endogeneity, two econometric challenges that have been insufficiently addressed in prior research. By distinguishing between developed and developing economies, the study further examines whether the emissions-reducing effect of environmental innovation is conditional on technological maturity and institutional capacity. The findings demonstrate that environmental innovation significantly reduces carbon emissions only in developed economies, highlighting that the effectiveness of green innovation is not universal but is contingent on the broader technological and institutional environment in which it operates. These results carry important implications for the design of differentiated climate and innovation policies across countries at varying stages of development.

The remainder of the paper is structured as follows. Section 2 reviews the relevant theoretical and empirical literature and identifies the research gaps this study seeks to address. Section 3 presents the hypotheses developed from the literature. Section 4 describes the data, variables, and econometric methodology. Section 5 Results. Section 6 discusses the empirical results. Section 7 conclusion and policy implications

2. LITERATURE REVIEW

The relationship between environmental innovation and carbon emissions has attracted substantial empirical attention, yet the accumulated evidence remains heterogeneous and, in several instances, contradictory. Divergences in methodological approaches, country samples, and innovation measures have produced a voluminous but inconsistent literature. The following review synthesises this evidence into two thematic strands: the direct innovation and emissions nexus and its broader contextual determinants, before identifying the specific gaps that motivate the present study.

The theoretical case for environmental innovation as a decarbonisation mechanism is well established. Innovation through cleaner production technologies, energy efficiency improvements, and renewable energy deployment is widely regarded as a primary instrument for decoupling economic growth from environmental degradation (Balsalobre-Lorente *et al.,*2021; Ullah *et al.,*2021). Empirically, however, the strength and direction of this relationship vary considerably across country contexts and estimation frameworks.

Among studies focused on advanced economies, the emissions-reducing effect of environmental innovation is relatively consistent. Aliani *et al.,*(2024) demonstrate that environment-related technology significantly reduced CO_2 emissions in G7 countries over 2000-2019. Fethi and Rahuman (2019) establish a significant long-run mitigation effect of eco-innovation in oil-exporting countries. Mensah *et* *al.,*(2018) similarly find that innovation plays a statistically significant mitigating role across 28 OECD countries, and Ponce and Khan (2021) establish that renewable energy and energy efficiency jointly contribute to emissions reductions across nine developed economies. In institutionally stable OECD settings, the environmental gains from innovation are generally more systematic and statistically reliable (Jiang, 2024; Tobelmann & Wendler, 2020).

In contrast, evidence from developing economies is considerably more mixed. Where governance quality is limited, regulatory frameworks are weakly enforced, or technological absorptive capacity is insufficient, the emissions-reducing potential of innovation is substantially constrained (Dash, 2024; Mensah *et al.,*2018). Du *et al.,*(2019), analysing 71 economies over 1996-2012 using threshold regression, find that green innovation significantly reduces CO_2 emissions only above a critical income threshold for lower-income economies; the effect is statistically insignificant. Chen and Lee (2020), employing spatial econometric models for 96 nations over 1996-2018, similarly find that innovation generates positive environmental spillovers only when originating from high-income, high-technology economies, while in lower-income settings, higher R&D intensity is paradoxically associated with increased emissions. These findings collectively suggest that the innovation–emissions relationship is inherently heterogeneous, shaped by income level, institutional quality, and technological maturity rather than uniform across country contexts.

A further dimension of complexity concerns the functional form of the relationship. A growing strand of the literature documents nonlinear dynamics consistent with the Innovation and Environmental Kuznets Curve hypothesis, in which innovation may initially increase emissions before crossing a threshold beyond which mitigation effects dominate (Razzaq *et al.,*2021; Ma *et al.,*2022). Linear estimation frameworks applied to heterogeneous country samples therefore risk systematically misrepresenting the true relationship between innovation and emissions. The literature also widely documents bidirectional causality between innovation and emissions, reflecting dynamic feedback in which elevated emissions motivate greater innovation investment, while innovation progressively reduces emissions (Thi & Do, 2024; Khattak *et al.,*2024). This reverse causality introduces the potential for endogeneity bias in conventional estimators, a concern that the present study directly addresses.

The effectiveness of environmental innovation in reducing emissions is not inherent but is mediated by broader economic and institutional conditions. Renewable energy deployment has been consistently identified as a critical complementary channel through which innovation translates into environmental gains (Shan *et al.,*2021; Wang *et al.,*2023). Well-designed policy instruments, including carbon pricing, environmental taxation, and stringent regulatory oversight, significantly enhance the capacity of innovation to reduce emissions, while weak or inconsistently enforced frameworks generate rebound effects that neutralise innovation's environmental benefits (Sharif *et al.,*2022; Khurshid, 2023; Chang *et al.,*2023). In emerging economies, financial development, green finance, and human capital accumulation have been identified as further enabling factors that strengthen the innovation and emissions nexus (Sadiq *et al.,*2024; Iqbal, 2024; Lisha *et al.,*2023). Collectively, these findings underscore that innovation operates within and is conditioned by the broader institutional and policy environment, making context-sensitive analysis essential for generating credible and policy-relevant empirical findings.

A critical appraisal of this literature reveals three important gaps that directly motivate the present study. First, the majority of existing studies impose a homogeneous, linear relationship between environmental innovation and CO_2 emissions across countries, overlooking the significant variation in technological readiness, institutional quality, and absorptive capacity that characterises different economies. Imposing a uniform effect across heterogeneous country contexts risks producing misleading estimates and obscuring the precise conditions under which innovation delivers its greatest environmental returns. Second, despite clear structural differences in innovation infrastructure, regulatory frameworks, and energy systems, there is limited evidence on whether the innovation-emissions nexus differs systematically between developed and developing economies. Treating these groups as a homogeneous bloc may conceal policy-relevant heterogeneity that is critical for the design of differentiated climate and innovation strategies. Third, the potential endogeneity of environmental innovation has received insufficient methodological attention. Countries facing higher emission intensities may simultaneously face stronger regulatory and reputational pressures to invest in green innovation, introducing reverse causality that conventional panel estimators fail to adequately address and raising serious concerns about the consistency of reported findings.

The present study addresses all three gaps by investigating the heterogeneous effects of environmental innovation on CO_2 emissions across countries, employing fixed-effects, Driscoll-Kraay, and instrumental variable estimators to account for cross-sectional dependence and endogeneity, and conducting disaggregated analysis for developed and developing economies to reveal whether innovation’s effectiveness is conditional on technological maturity and institutional capacity.

3. Research Hypotheses

Drawing on the theoretical arguments and empirical evidence reviewed in Section 2, and in direct response to the three identified research gaps, the following hypotheses are developed to guide the empirical analysis.

H1: Environmental innovation has a significant negative effect on CO_2 emissions across countries.
H2a: The emissions-reducing effect of environmental innovation is weaker or statistically insignificant in developing countries.
H2b: Environmental innovation significantly reduces CO_2 emissions in developed countries.
H3: There is significant reverse causality between environmental innovation and CO_2 emissions, whereby higher emission levels stimulate greater innovation investment, introducing endogeneity bias in conventional panel estimators.

4. DATA, VARIABLES, AND ECONOMETRIC METHODOLOGY

4.1 Data and Variables

This study examines the relationship between environmental innovation and carbon emissions using an unbalanced panel of 61 countries over 22 years, yielding 1342 observations. The sample is further disaggregated into 27 developing countries and 34 developed countries to assess whether the innovation-emissions nexus differs by development status. The dependent variable is $PCCO_2$, measured as the logarithm of carbon emissions per capita. The key explanatory variable is Environmental Innovation (SERP), defined as the log of the environment-related patents stock. We construct the stock of environment-related patents using a 15% depreciation rate, as suggested by Griliches (1979) and Hall *et al.,*(2010). The control variables include PCG, the logarithm of per capita GDP; PCG2, the square of PCG to capture potential nonlinearity in the income and emissions relationship; TRADE, measured as exports plus imports relative to GDP; FDI, foreign direct investment net inflows as a share of GDP; and Urbanisation, measured as the urban population share of total population. These definitions are consistent with the variable descriptions reported in Table 1.

Table 1: Description of Variables

Variables	Measurements	Source
$PCCO_2$	Log of Carbon emissions in tonnes / Capita	Organisation for Economic Co-operation and Development
SERP	(Stock of Environment-Related Patent / Stock of Total Patent) *100	Organisation for Economic Co-operation and Development
PCG	Log of per capita GDP	World Development Indicator, World Bank
PCG2	Square of PCG	Author Calculation
TRADE	(Export + Import)/ GDP	World Development Indicator, World Bank
FDI	Foreign Direct Investment, net inflow % of GDP	World Development Indicator, World Bank
Urbanization	Urban Population (% of Total Population)	World Development Indicator, World Bank

4.2 Econometric Methodology

The econometric analysis is conducted in three stages. First, fixed-effects models are estimated to control for unobserved time-invariant country-specific heterogeneity (Wooldridge, 2010; Baltagi, 2021). Second, Driscoll–Kraay standard errors are used to obtain inference that is robust to cross-sectional dependence, serial correlation, and heteroskedasticity (Driscoll & Kraay, 1998; Hoechle, 2007). Third, a fixed-effects instrumental-variable (FE-IV/2SLS) specification is estimated to address possible endogeneity in environmental innovation (Angrist & Pischke, 2009).

To examine the impact of environmental innovation on per capita CO_2 emissions, this study employs a panel data framework that accounts for country-specific heterogeneity and potential endogeneity. The baseline specification is estimated using a fixed-effects (FE) model, which controls for unobserved time-invariant characteristics across countries. The empirical model is specified as follows:
The baseline specification can be written as:

$$PCCO_{2it} = \alpha_i + \beta_1 SERP_{it} + \beta_2 PCG_{it} + \beta_3 PCG2_{it} + \beta_4 TRADE_{it} + \beta_5 FDI_{it} + \beta_6 Urbanisation_{it} + \varepsilon_{it} \quad (1)$$

where α_i captures country fixed effects and ε_{it} is the idiosyncratic error term. The squared income term allows for a nonlinear environmental Kuznets curve relationship between economic growth and emissions, while the disaggregated estimations for developed and developing countries permit direct comparison of heterogeneous effects across country groups.

Although the fixed-effects estimator controls for unobserved heterogeneity, the presence of heteroskedasticity, serial correlation, and cross-sectional dependence may bias conventional standard errors.

Therefore, following Driscoll and Kraay (1998), Driscoll-Kraay standard errors are employed to obtain robust statistical inference. This estimator provides consistent standard errors in the presence of cross-sectional dependence and temporal correlation, which are common features of macro-panel datasets.

A further econometric concern relates to the potential endogeneity of environmental innovation. Countries with higher carbon emissions may respond by increasing investments in environmental technologies and green innovation, creating a reverse-causality problem. To address this issue, a fixed-effects instrumental variable two-stage least squares (FE-IV/2SLS) estimator is employed. To address potential endogeneity concerns, this study employs the one-period lag of environmental innovation and the logarithm of per capita R&D stock as instrumental variables for environmental innovation. The selection of these instruments is guided by both theoretical and empirical considerations and is intended to satisfy the key requirements of instrument validity, namely relevance and exogeneity (Angrist & Pischke, 2009; Bøler *et al.,*2015; Bellemare *et al.,*2017). The lagged value of environmental innovation captures the persistent and cumulative nature of technological development, while the stock of per capita R&D reflects a country's innovation capacity and potential for knowledge creation. Both instruments are expected to be strongly correlated with environmental innovation, but are unlikely to directly influence current CO_2 emissions after accounting for country-specific effects and other control variables.

The first-stage regression is specified as:

$$SERP_{it} = \alpha_i + \alpha_1 SERP_{it-1} + \alpha_2 \ln SRD_{it} + \alpha_3 PCG_{it} + \alpha_4 PCG2_{it} + \alpha_5 TRADE_{it} + \alpha_6 FDI_{it} + \alpha_7 Urbanisation_{it} + \varepsilon_{it} \quad (2)$$

Second-stage regression is specified as:

$$PCCO_{2it} = \gamma_i + \beta_1 \widehat{SERP}_{it} + \beta_2 PCG_{it} + \beta_3 PCG2_{it} + \beta_4 TRADE_{it} + \beta_5 FDI_{it} + \beta_6 Urbanisation_{it} + \vartheta_{it} \quad (3)$$

The validity of the instruments is assessed using the Kleibergen-Paap under-identification and weak-instrument tests, while the Hansen J-statistic is used to examine the instruments' exogeneity. The reported diagnostic statistics confirm that the instruments are relevant and valid, thereby supporting the consistency of the FE-IV/2SLS estimates.

4.3 Descriptive Statistics and Multicollinearity Analysis

The descriptive statistics present in Table 2 indicate substantial cross-country variation in the core variables, which supports the use of a panel framework. The mean value of $PCCO_2$ is 1.889, with a range of 0.438 to 3.245, while SERP has a mean of 9.637, with a minimum of 3.234 and a maximum of 22.665. The dispersion in TRADE, FDI, and Urbanisation further suggests meaningful heterogeneity across countries and over time. Multicollinearity does not appear to be a serious concern, as the mean VIF is 1.45 and the highest individual VIFs remain well below conventional thresholds (Table 3).

Table 2: Panel Descriptive Statistics

Variables		Mean	Std. dev.	Min	Max	Observation
$PCCO_2$	overall	1.889	0.568	0.438	3.245	N=1342
	between		0.558	0.556	2.961	n=61
	within		0.125	1.239	2.240	T=22
SERP	overall	9.637	3.137	3.234	22.665	N=1342
	between		2.443	5.564	18.074	n=61
	within		1.991	2.347	18.036	T=22
PCG	overall	9.630	1.061	6.627	11.630	N=1342
	between		1.054	7.128	11.553	n=61
	within		0.183	8.730	10.362	T=22
PCG2	overall	93.872	20.054	43.922	135.256	N=1342
	between		19.952	50.913	133.465	n=61
	within		3.212	78.934	106.715	T=22
TRADE	overall	95.746	68.698	19.560	442.620	N=1342
	between		67.363	26.615	362.920	n=61
	within		15.896	-22.513	179.258	T=22
FDI	overall	6.511	19.858	-101.833	279.361	N=1342
	between		11.661	0.339	72.920	n=61
	within		16.139	-168.242	212.952	T=22
Urbanisation	overall	71.628	16.594	18.196	100.000	N=1342
	between		16.548	18.352	100.000	n=61
	within		2.412	57.928	84.563	T=22

Source: Author's Calculation

Table 3: Variance Inflation Factors (VIF)

Variables	VIF	1/VIF

PCG	1.95	0.512
Urbanisation	1.95	0.513
TRADE	1.2	0.833
FDI	1.14	0.881
SERP	1.01	0.985
Mean VIF	1.45	

Source: Author's Calculation

5. RESULTS

5.1 Baseline Regression Result of Environmental Innovation and CO_2 Emissions: Full Sample

Table 4 reports the fixed-effects and Driscoll-Kraay estimations for the full sample of 61 countries. The coefficient of environmental innovation (SERP) is negative and statistically significant at the 1% level across all specifications. In the preferred Driscoll-Kraay model, a one-unit increase in environmental innovation reduces per capita CO_2 emissions by approximately 1.7 per cent, holding other factors constant. This finding provides strong support for Hypothesis 1 and suggests that environmental innovation contributes significantly to environmental improvement.

The results further reveal that per capita income (PCG) has a positive and significant effect on emissions, whereas the squared income term (PCG2) is negative and significant. This combination of coefficients indicates the existence of an inverted U-shaped Environmental Kuznets Curve (EKC) as suggested by Grossman & Krueger (1995), implying that emissions initially increase with economic growth but decline after a certain income threshold is reached. Trade openness exerts a negative and significant effect on emissions, suggesting that greater integration into international markets may facilitate cleaner production practices and technology diffusion. Foreign direct investment does not appear to have a statistically significant effect, while urbanisation exhibits a weak negative effect that becomes insignificant under the more robust Driscoll-Kraay specification.

Table 4: Environmental Innovation and $PCCO_2$ Emissions: Fixed Effect and Driscoll-Kraay Estimation for the Full Sample

	Fixed Effects Analysis		Driscoll-Kraay Standard Error	
Variables	1	2	3	4
SERP	-0.0183*** [0.0017]	-0.0166*** [0.0017]	-0.0183*** [0.0032]	-0.0166*** [0.0027]
PCG	2.574*** [0.1588]	2.3966*** [0.1599]	2.574*** [0.3565]	2.3966*** [0.3801]
PCG2	-0.1301*** [0.0091]	-0.1185*** [0.0092]	-0.1301*** [0.0213]	-0.1185*** [0.0218]
TRADE		-0.0012*** [0.0002]		-0.0012*** [0.0003]
FDI		-0.0002 [0.0002]		-0.0002 [0.0002]
Urbanisation		-0.0027* [0.0014]		-0.0027 [0.0036]
Cons.	-10.507*** [0.6888]	-9.6004*** [0.6929]	-10.507*** [1.4419]	-9.6004*** [1.4193]
R-Squared	0.2992	0.3222	0.2992	0.3222
Obs.	1342	1342	1342	1342
Country	61	61	61	61

Standard error in [] Parentheses *** p<0.01, ** p<0.05, * p<0.1
Source: Author's Calculation

5.2 Divergent Effects of Environmental Innovation on $PCCO_2$ Emissions across Developing and Developed Countries

Table 5 presents the results for developing economies. Unlike the full-sample estimates, environmental innovation does not exert a statistically significant effect on carbon emissions in either the fixed-effects or Driscoll-Kraay models. Consequently, no empirical support is found for a direct role of environmental innovation in reducing emissions in developing countries.

The income variables continue to support the EKC hypothesis, with per capita income positively associated with emissions, and its squared term negatively associated. Urbanisation shows a positive, statistically significant coefficient, indicating that urban expansion contributes to higher emissions in developing economies. In contrast, trade openness and foreign direct investment remain statistically insignificant. Overall, the results suggest that structural and institutional constraints may limit the effectiveness of environmental innovation in reducing emissions in developing countries.

Table 5: Environmental Innovation and PCCO₂ Emissions: Fixed Effect and Driscoll-Kraay Estimation for the Developing Countries

	Fixed Effects Analysis		Driscoll-Kraay Standard Error	
Variables	1	2	3	4
SERP	0.001 [0.002]	0.0012 [0.002]	0.001 [0.0016]	0.0012 [0.0018]
PCG	0.8798*** [0.2083]	1.0193*** [0.2122]	0.8798** [0.3336]	1.0193*** [0.2737]
PCG2	-0.0321** [0.0124]	-0.0429*** [0.0128]	-0.0321 [0.02]	-0.0429** [0.0155]
TRADE		-0.0003 [0.0003]		-0.0003 [0.0003]
FDI		0.0005 [0.0006]		0.0005 [0.001]
Urbanisation		0.0046*** [0.0016]		0.0046** [0.0022]
Cons.	-3.661*** [0.8734]	-4.3262*** [0.901]	-3.661** [1.3724]	-4.3262*** [1.084]
R-Squared	0.4804	0.4907	0.4804	0.4907
Obs.	594	594	594	594
Country	27	27	27	27

Standard error in [] Parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$
Source: Author's Calculation

Regression results for developed economies are presented in Table 6. Environmental innovation exhibits a negative and highly significant coefficient across all model specifications. The magnitude of the coefficient is larger than that observed in the full sample, indicating that environmental innovation generates stronger environmental benefits in developed countries. Specifically, an increase in environmental innovation activity significantly reduces per capita carbon emissions.

The income variables again confirm the presence of the EKC hypothesis. Trade openness contributes significantly to emissions reduction, while foreign direct investment remains insignificant. Urbanisation displays a negative and significant coefficient, suggesting that highly urbanised developed economies may benefit from economies of scale, advanced infrastructure, and cleaner technologies that collectively improve environmental outcomes. These findings provide strong support for Hypothesis 2b.

Table 6: Environmental Innovation and PCCO₂ Emissions: Fixed Effect and Driscoll-Kraay Estimation for the Developing Countries

	Fixed Effects Analysis		Driscoll-Kraay Standard Error	
Variables	1	2	3	4
SERP	-0.0339*** [0.0025]	-0.026*** [0.0026]	-0.0339*** [0.0055]	-0.026*** [0.005]
PCG	3.7449*** [0.5527]	3.5307*** [0.5309]	3.7449*** [0.646]	3.5307*** [0.5775]
PCG2	-0.1888*** [0.0282]	-0.1746*** [0.027]	-0.1888*** [0.0365]	-0.1746*** [0.0327]
TRADE		-0.0012*** [0.0002]		-0.0012** [0.0004]
FDI		-0.0002 [0.0002]		-0.0002 [0.0002]
Urbanisation		-0.0173*** [0.0027]		-0.0173** [0.0077]
Cons.	-15.9879*** [2.7106]	-13.8812*** [2.652]	-15.9879*** [2.8207]	-13.8812*** [2.5379]
R-Squared	0.3411	0.4156	0.3411	0.4156
Obs.	748	748	748	748
Country	34	34	34	34

Standard error in [] Parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Source: Author's Calculation

5.3 Robustness Analysis: FE-IV Estimation

To address potential endogeneity in environmental innovation, Table 7 reports results from fixed-effects instrumental-variable (FE-IV) estimation. The coefficient of environmental innovation remains negative and statistically significant for the full sample and the developed-country subsample, confirming the robustness of the baseline findings. However, environmental innovation remains statistically insignificant in developing economies.

The diagnostic statistics support the validity of the instrumental variable approach. The Kleibergen-Paap LM statistics reject the null of under-identification, indicating that the instruments are relevant, while the corresponding Wald F-statistics indicate that the instruments are extremely strong, and no weak instrument problem exists. Furthermore, the Hansen J statistics suggest that the overidentifying restrictions are valid or that the instruments are valid. These results reinforce the conclusion that environmental innovation contributes to emissions reduction primarily in developed economies.

Table 7: Environmental Innovation and PCCO$_2$ Emissions: FE-IV (2SLS) Regression Estimation

Variables	All Countries	Developing Countries	Developed Countries
SERP	-0.0204*** [0.0071]	-0.0002 [0.0046]	-0.0325*** [0.0074]
PCG	2.5622*** [0.5773]	1.1872* [0.6502]	3.095*** [1.1697]
PCG2	-0.1261*** [0.0319]	-0.0514 [0.0394]	-0.1511** [0.0597]
TRADE	-0.0012** [0.0006]	-0.0003 [0.0007]	-0.0013 [0.0008]
FDI	-0.0001 [0.0002]	0.0006 [0.0008]	-0.0002 [0.0002]
Urbanisation	-0.0039 [0.0042]	0.0033 [0.0044]	-0.0178* [0.01]
R-Squared	0.3214	0.4726	0.423
Obs.	1281	567	714
Country	61	27	34
Model Diagnostic			
Fixed Effects	YES	YES	YES
Clustered Standard Errors	Yes	Yes	Yes
F-statistic	6.23***	9.94***	10.24***
Kleibergen–Paap rk LM statistic	21.59***	9.29***	12.91***
Kleibergen–Paap rk Wald F statistic	1865.33	604.05	1314.28
Hansen J statistic	0.09	0.548	2.369

Standard error in [] Parentheses *** p<0.01, ** p<0.05, * p<0.1

Source: Author's Calculation

6. DISCUSSION

The empirical findings provide important insights into the heterogeneous relationship between environmental innovation and carbon emissions. Consistent with Hypothesis 1, environmental innovation significantly reduces CO_2 emissions when all countries are considered together. This result supports the theoretical argument that green technological progress improves resource efficiency, promotes cleaner production processes, and facilitates the transition towards low-carbon economic systems (Balsalobre-Lorente *et al.,*2021; Ullah *et al.,*2021). The finding is also consistent with previous studies that document the emissions-reducing role of environmental innovation in advanced economies, including Aliani *et al.,* (2024), Fethi and Rahuman (2019), and Mensah *et al.,* (2018).

A key contribution of this study is the identification of substantial heterogeneity across country groups. Environmental innovation is found to be effective only in developed economies, whereas its effect is statistically insignificant in developing economies. This outcome supports Hypotheses 2a and 2b and suggests that the environmental benefits of innovation are conditional upon broader institutional and technological factors. Developed economies generally possess stronger innovation ecosystems, better regulatory enforcement, higher technological absorptive capacity, and more mature environmental governance structures. These characteristics enable environmental innovations to be successfully commercialised and integrated into production systems, thereby generating measurable reductions in emissions. In contrast, developing economies often face institutional weaknesses, financing constraints, inadequate technological infrastructure, and lower absorptive capacity. As a result, environment-related patents and innovation activities may not translate directly into widespread adoption of cleaner technologies. This finding is consistent with the arguments advanced by Du *et al.,*(2019), Chen and Lee (2020), and Dash (2024), who emphasise that the effectiveness of environmental innovation depends critically on economic development, institutional quality, and technological readiness.

The confirmation of the Environmental Kuznets Curve hypothesis across most specifications further suggests that economic development plays a crucial role in shaping environmental outcomes. While economic growth initially increases emissions, rising income levels eventually facilitate structural transformation, cleaner technologies, and stronger environmental regulations that reduce environmental degradation. This result aligns with a substantial body of environmental economics literature (Grossman & Krueger, 1995) and reinforces the importance of sustainable development pathways.

The robustness of the findings under the instrumental variable framework is particularly important. The persistence of the negative innovation coefficient after addressing endogeneity concerns indicates that the observed relationship is unlikely to be driven by reverse causality. Rather than emissions simply inducing greater innovation efforts, the evidence suggests that environmental innovation itself contributes to emissions mitigation, particularly in technologically advanced economies. This finding strengthens the causal interpretation of the results and addresses a major limitation identified in previous studies.

Overall, the findings demonstrate that environmental innovation is not universally effective. Its environmental impact depends on the economic, technological, and institutional context in which it operates. Consequently, policies aimed at promoting environmental innovation should be complemented by broader measures that strengthen technological capabilities, institutional quality, and the diffusion of clean technologies, particularly in developing economies. This heterogeneous perspective provides a more nuanced understanding of the innovation-CO_2 emissions nexus and contributes to the growing literature on sustainable development and climate policy.

7. CONCLUSION

This study explored the influence of environmental innovation on carbon dioxide (CO_2) emissions across 61 countries from 2000 to 2021, using a robust econometric framework that included fixed-effects, Driscoll-Kraay, and instrumental-variable estimators. It highlighted three primary conclusions: First, environmental innovation significantly lowers per capita CO_2 emissions overall, indicating that technological advancements toward environmental goals enhance ecological quality. Second, the effectiveness of such innovations differs markedly between developed and developing countries; while they effectively reduce emissions in developed nations, the impact is statistically insignificant in developing ones. Third, the study's instrumental-variable results confirm these findings, suggesting that the relationship is not influenced by endogeneity bias. Additionally, the research supports the Environmental Kuznets Curve (EKC) hypothesis, revealing that economic growth can initially lead to increased emissions before fostering environmental improvement at higher income levels. Overall, the study emphasises that environmental innovation must be paired with appropriate institutional frameworks, technological capabilities, and sound governance to achieve substantial emissions reductions, underscoring the need to account for cross-country heterogeneity in assessing environmental innovation and sustainability.

7.1 Policy Implications

The findings have several policy implications. First, developed economies should continue investing in environmental R&D, green patents, renewable energy technologies, and energy-efficient innovations to accelerate progress toward net-zero emissions. Second, developing countries should complement innovation policies with stronger institutions, effective environmental regulations, improved human capital, greater access to green finance, and enhanced technological infrastructure to maximise the environmental benefits of innovation. Third, international technology transfer and climate cooperation are essential to help developing economies overcome financial and technological constraints and facilitate the adoption of cleaner technologies. Fourth, policies promoting trade openness can support emissions reduction through technology diffusion and cleaner production practices. Finally, climate and innovation policies should be tailored to countries' levels of technological capability, institutional quality, and economic development, as the effectiveness of environmental innovation varies across different contexts.

Declaration of Generative AI and AI-assisted technologies in the writing process:

During the preparation of this work, the author(s) used ChatGPT in order to improve readability and linguistic clarity. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

REFERENCES

- Aliani, K., Borgi, H., Alessa, N., Hamza, F., & Albitar, K. (2024). The Impact of Green Innovation and Renewable Energy on CO_2 Emissions in G7 Nations. *Heliyon, 10*, e31142. https://doi.org/10.1016/j.heliyon.2024.e31142
- Angrist, J. D., & Pischke, J. S. (2009). *Mostly harmless econometrics: An empiricist's companion*. Princeton University Press.
- Balsalobre-Lorente, D., Shahbaz, M., Roubaud, D., & Farhani, S. (2018). How economic growth, renewable electricity and natural resources contribute to CO2 emissions? *Energy Policy*, *113*, 356-367. https://doi.org/10.1016/j.enpol.2017.10.050
- Baltagi, B. H. (2021). *Econometric analysis of panel data* (6th ed.). Springer. https://doi.org/10.1007/978-3-030-53953-5
- Bellemare, M. F., Masaki, T., & Pepinsky, T. B. (2017). Lagged Explanatory Variables and the Estimation of Causal Effect. *The Journal of Politics*. https://doi.org/10.1086/690946
- Bøler, E. A., Moxnes, A., & Ulltveit-Moe, K. H. (2015). R&D, international sourcing, and the joint impact on firm performance. *American Economic Review, 105*(12), 3704–3739. https://doi.org/10.1257/aer.20121530
- Chang, K., Liu, L., Luo, D., & Xing, K. (2023). The impact of green technology innovation on carbon dioxide emissions: The role of local environmental regulations. *Journal of Environmental Management, 340*, 117990. https://doi.org/10.1016/j.jenvman.2023.117990
- Chen, Y., & Lee, C.-C. (2020). Does technological innovation reduce CO_2 emissions? Cross-country evidence. *Journal of Cleaner Production, 263*, 121550. https://doi.org/10.1016/j.jclepro.2020.121550
- Dash, A. K., Panda, S. P., Sahu, P. K., & Jóźwik, B. (2024). Do green innovation and governance limit CO_2 emissions: Evidence from twelve polluting countries with panel data decision tree model. *Discover Sustainability, 5*, 198. https://doi.org/10.1007/s43621-024-00418-9
- Driscoll, J. C., & Kraay, A. C. (1998). Consistent covariance matrix estimation with spatially dependent panel data. *The Review of Economics and Statistics*, 80(4), 549–560. https://doi.org/10.1162/003465398557825
- Du, K., Li, P., & Yan, Z. (2019). Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data. *Technological Forecasting and Social Change*, *146*, 297-303. https://doi.org/10.1016/j.techfore.2019.06.010
- Energy Institute. (2023). *Statistical Review of World Energy 2023*. https://www.energyinst.org/statistical-review
- Fethi, S., & Rahuma, A. (2019). The role of eco-innovation on CO_2 emission reduction in an extended version of the environmental Kuznets curve: Evidence from the top 20 refined oil exporting countries. *Environmental Science and Pollution Research, 26*(30), 30145–30153. https://doi.org/10.1007/s11356-019-05951-z
- Griliches, Z. (1979). Issues in assessing the contribution of R&D to productivity growth. *Bell Journal of Economics, 10*(1), 92–116. https://doi.org/10.2307/3003321
- Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *Quarterly Journal of Economics, 110*(2), 353–377. https://doi.org/10.2307/2118443
- Hall, J. K., Daneke, G. A., & Lenox, M. J. (2010). Sustainable development and entrepreneurship: Past contributions and future directions. *Journal of Business Venturing*, *25*(5), 439-448. https://doi.org/10.1016/j.jbusvent.2010.01.002
- Hoechle, D. (2007). Robust standard errors for panel regressions with cross-sectional dependence. *Stata Journal*, 7(3), 281–312. https://doi.org/10.1177/1536867X0700700301
- Hordofa, T. T., Vu, H. M., Maneengam, A., Purnomo, E. P., Cong, P. T., & Liying, S. (2023). Does eco-innovation and green investment limit the CO_2 emissions in China? *Economic Research-Ekonomska Istraživanja, 36*(1), 634–649. https://doi.org/10.1080/1331677X.2022.2116067
- Iqbal, K., Hassan, S. T., Geng, Y., & Cai, C. (2024). Impact of green technological innovations, ICT, and renewable energy on CO_2 emissions in emerging economies. *International Journal of Energy Research, 2024*, Article ID 5594324. https://doi.org/10.1155/er/5594324
- Jiang, Y., Hossain, M. R., Khan, Z., Chen, J., & Badeeb, R. A. (2024). Revisiting research and development expenditures and trade-adjusted emissions: Green innovation and renewable energy R&D role for developed countries. *Journal of the Knowledge Economy, 15*, 2156–2191. https://doi.org/10.1007/s13132-023-01220-0\
- Khan, H., Khan, I., & BiBi, R. (2022). The Role of Innovation and Renewable Energy Consumption in Reducing Environmental Degradation in OECD Countries. *Environmental Science and Pollution Research, 29*(43), 43800–43813. https://doi.org/10.1007/s11356-022-18912-w
- Khattak, S. I., Ahmad, M., Khan, Z. U., & Khan, A. (2020). Exploring the impact of innovation, renewable energy consumption, and income on CO_2 emissions: New evidence from the BRICS economies. *Environmental Science and Pollution Research, 27*(12), 13866–13881. https://doi.org/10.1007/s11356-020-07876-4
- Khattak, S. I., Khan, A., & Hussain, K. (2024). Green technology innovations, natural gas and resource extraction strategies in BRICS: Modelling impacts on CO_2 emission intensity. *Sustainable*

Futures, 7, 100227. https://doi.org/10.1016/j.sftr.2024.100227

- Khurshid, A., Rauf, A., Qayyum, S., Calin, A. C., & Duan, W. (2023). Green innovation and carbon emissions: The role of carbon pricing and environmental policies in attaining sustainable development targets of carbon mitigation-Evidence from Central-Eastern Europe. *Environment, Development and Sustainability, 25*, 8777–8798. https://doi.org/10.1007/s10668-022-02422-3
- Lisha, L., Mousa, S., Arnone, G., Muda, I., Huerta-Soto, R., & Shiming, Z. (2023). Natural resources, green innovation, fintech, and sustainability: A fresh insight from BRICS. *Resources Policy, 80*, 103119. https://doi.org/10.1016/j.resourpol.2022.103119
- Ma, X., Arif, A., Kaur, P., Jain, V., Said, L. R., & Mughal, N. (2022). Revealing the effectiveness of technological innovation shocks on CO_2 emissions in BRICS: emerging challenges and implications. *Environmental Science and Pollution Research, 29*(35), 47373–47381. https://doi.org/10.1007/s11356-022-19053-w
- Mensah, C. N., Long, X., Boamah, K. B., Bediako, I. A., Dauda, L., & Salman, M. (2018). The effect of innovation on CO_2 emissions of OECD countries from 1990 to 2014. *Environmental Science and Pollution Research, 25*(30), 29678–29698. https://doi.org/10.1007/s11356-018-2968-0
- Ponce, P., & Khan, S. A. R. (2021). A causal link between renewable energy, energy efficiency, property rights, and CO_2 emissions in developed countries: A road map for environmental sustainability. *Environmental Science and Pollution Research, 28*, 37804–37817. https://doi.org/10.1007/s11356-021-12465-0
- Razzaq, A., Wang, Y., Chupradit, S., Suksatan, W., & Shahzad, F. (2021). Asymmetric inter-linkages between green technology innovation and consumption-based carbon emissions in BRICS countries using quantile-on-quantile framework. *Technology in Society, 66*, 101656. https://doi.org/10.1016/j.techsoc.2021.101656
- Sadiq, M., Chau, K. Y., Ha, N. T. T., Phan, T. T. H., Ngo, T. Q., & Huy, P. Q. (2024). The impact of green finance, eco-innovation, renewable energy and carbon taxes on CO_2 emissions in BRICS countries: Evidence from CS ARDL estimation. *Geoscience Frontiers, 15*, 101689. https://doi.org/10.1016/j.gsf.2023.101689
- Salahuddin, M., Gow, J., & Ozturk, I. (2015). Is the long-run relationship between economic growth, electricity consumption, carbon dioxide emissions and financial development in Gulf Cooperation Council countries robust? *Renewable and Sustainable Energy Reviews, 51*, 317–326. https://doi.org/10.1016/j.rser.2015.06.005
- Shan, S., Genç, S. Y., Kamran, H. W., & Dinca, G. (2021). Role of green technology innovation and renewable energy in carbon neutrality: A sustainable investigation from Turkey. *Journal of Environmental Management, 294*, 113004. https://doi.org/10.1016/j.jenvman.2021.113004
- Sharif, A., Saqib, N., Dong, K., & Khan, S. A. R. (2022). Nexus between green technology innovation, green financing, and CO_2 emissions in the G7 countries: The moderating role of social globalisation. *Sustainable Development, 30*(6), 1934–1946. https://doi.org/10.1002/sd.2360
- Thi, D. M.-T. T., & Do, T. T.-P. (2024). The interrelationships between carbon dioxide emissions and innovation: International evidence. *International Journal of Sustainable Energy, 43*(1), 2352515. https://doi.org/10.1080/14786451.2024.2352515
- Tobelmann, D., & Wendler, T. (2020). The impact of environmental innovation on carbon dioxide emissions. *Journal of Cleaner Production, 244*, 118787. https://doi.org/10.1016/j.jclepro.2019.118787
- Ullah, F., Qayyum, S., Thaheem, M. J., Al-Turjman, F., & Sepasgozar, S. M. E. (2021). Risk Management in Sustainable Smart City Governance: A TOE Framework. *Technological Forecasting and Social Change, 167*, 120743. https://doi.org/10.1016/j.techfore.2021.120743
- Wang, Z., Sami, F., Khan, S., Alamri, A. M., & Zaidan, A. M. (2023). Green Innovation and Low Carbon Emissions in OECD Economies: The Role of Sustainable Energy Technology in Achieving Carbon Neutrality Targets. *Sustainable Energy Technologies and Assessments, 59*, 103401. https://doi.org/10.1016/j.seta.2023.103401
- Wooldridge, J. M. (2010). *Econometric Analysis of Cross-Section and Panel Data* (2nd ed.). MIT Press.