RESEARCH ARTICLE

Navigating Growth and Sustainability: Technological Advances, Renewable Energy, and Environmental Quality

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Abstract
The rise in economic growth driven by increased production and industrialization has led to greater energy demand, which in turn has caused higher carbon emissions and a deterioration in environmental quality. Technological innovations aimed at improving energy efficiency, enhancing production efficiency, and utilizing renewable energy in industrial processes offer potential solutions to address environmental degradation. This study investigates the impact of technological innovations, renewable energy consumption, and economic growth on environmental degradation in OECD countries from 1989 to 2024. Using fixed effects and a two-step generalized method of moments, the findings indicate that economic growth and high technology exports negatively impact environmental quality, while patent applications and R&D efforts significantly reduce emissions. The Innovation Claudia curve is confirmed through the squared term of the innovation indicator, although the innovation index itself is found to have a positive impact on carbon emissions. Notably, the study concludes that increasing the adoption of renewable energy sources leads to substantial improvements in environmental quality. These findings have important implications for the governments of the countries studied.

Keywords: Technological innovations; renewable energy consumption; economic growth; Environmental sustainability

Introduction

Economic growth is widely recognized as a key driver of carbon dioxide emissions, particularly in less developed and emerging economies. As economic activities increase, so does energy demand, leading to higher carbon dioxide emissions (Su et al., 2021; Tariq et al., 2017; Mehmood, 2021). Countries pursue economic growth to improve living standards (Esso & Keho, 2016; Deviren & Deviren, 2016), but reliance on nonrenewable energy sources during periods of economic expansion results in increased carbon emissions (Sharma, Shahbaz, Kautish, and Vo, 2021). In contrast, renewable energy is environmentally friendly and plays a crucial role in slowing environmental degradation. However, most nations have yet to achieve the desired level of renewable energy use in economic activities, a critical goal for sustainable development. Both developing and developed countries have acknowledged the need to balance economic growth with environmental quality to ensure sustainable development (Wang et al., 2018). Achieving sustainable development goals can improve living standards, enhance environmental quality, and conserve energy (L. Li et al., 2011). Many countries have designed climate action strategies under the Paris Agreement to promote environmental sustainability but have also recognized the necessity of integrating renewable energy sources and green technological innovations (Florence Twum Appiah, 2021). While renewable energy and energy efficiency can reduce pollution, modern technologies and innovations are essential for improving energy efficiency. Technological advancements can play a pivotal role in reducing environmental degradation (Mensah, Long et al., 2018; Albino, Ardito et al., 2014; Raiser, Naims et al., 2017; Zhang, Peng et al., 2017; Sharma, Shahbaz, 2021). However, a critical gap in the literature exists regarding the dual role of technological advancements. While many studies suggest that technological innovation can improve energy efficiency and reduce emissions, others argue that innovations may, in fact, worsen environmental quality by increasing carbon emissions through industrial activities (Ahmad Khattak et al., 2020; Chien et al., 2021). This contradiction leaves a significant research gap: the complex relationship between technological innovation, renewable energy consumption, and environmental quality remains underexplored. Additionally, there has been limited empirical investigation into the non-linear relationship between technological innovation and carbon emissions, often referred to as the "Innovation Claudia Curve." This theory posits that technological advancements may initially increase emissions but eventually reduce them once a critical level of innovation is reached, yet empirical evidence for this curve, particularly in OECD countries, is scarce.

To address these gaps, the present study investigates the impact of technological innovations, renewable energy consumption, and economic growth on carbon dioxide emissions in OECD countries from 1989 to 2024. The research seeks to answer several key questions: Do technological advancements contribute to higher CO2 emissions? Is there a non-linear relationship between technological innovation and CO2 emissions? What factors lead to improvements in environmental quality? This study also aims to identify weak indicators of technological innovation in relation to environmental improvement and provides insights into how technological advancements can be leveraged to improve energy efficiency, increase the adoption of renewable energy, and enhance environmental quality.By examining the individual effects of technological innovation, renewable energy adoption, and economic growth, this study offers a nuanced understanding of the environmental impacts of technological progress. It extends the current literature by empirically validating the Innovation Claudia Curve and providing policy implications to help both developing and developed countries achieve their sustainable development goals. The remainder of this study is organized as follows: Section 2 reviews the relevant literature, Section 3 presents the research methodology, Section 4 discusses the results, and Section 5 concludes with policy implications.

Literature review

Although the majority of researchers, such as Raiser et al. (2017) and Y.-J. Zhang et al. (2017), argue that technological innovation positively influences environmental quality, past research has produced mixed findings regarding its impact. Despite the general consensus on the benefits of technological innovation, a clear understanding has yet to emerge due to variations in proxies for innovation, methods, data samples, and other factors, leading to contradictory results. For instance, Shan, Genc, Kamran, and Dinca (2021) examined the role of innovation and renewable energy in Turkey's carbon neutrality efforts using the STIRPAT model on data from 1990 to 2018. Their results indicated that while economic growth, population expansion, and energy consumption negatively affected environmental quality, increased innovation and renewable energy usage helped reduce carbon dioxide emissions. In a similar study, Suki, Sharif, Afshan, and Jermsittiparsert (2022) analyzed the relationship between renewable energy technology and carbon emissions in Malaysia, employing the BARDL model. They found that technological development contributed to a significant reduction in carbon emissions, thus improving environmental quality.

Similarly, Bilal, Li, and colleagues (2022) explored the relationship between green technology innovation, globalization, and carbon emissions in Belt and Road Initiative countries, using data from 1991 to 2019. They discovered a negative correlation between carbon emissions and technological innovation across South Asia, Southeast Asia, West Asia, Central and European countries, and North Africa, showing a consistent reduction in emissions due to technological advancements. Cheng, Sinha, and others (2021) analyzed data from 48 countries between 1971 and 2015 to investigate the link between technological innovation and economic growth. They found that the relationship between economic growth, financial innovation, and overall innovation varies across income levels and periods studied. This highlights the dynamic and context-dependent nature of technological advancements. Further evidence was provided by Abid, Mehmood, Tariq, and Haq (2021), who explored the connections between carbon emissions, energy use, and technological innovation in G8 countries between 1990 and 2019. Using FMOLS models, they demonstrated a negative relationship between technological innovation and carbon emissions, showing that innovation reduces emissions over time. Their research also highlighted how urbanization negatively affects environmental quality. Mikiewicz (2021) investigated the impact of innovation and technological advancements on emissions in Visegrad Group countries from 2000 to 2019, employing DOLS and FMOLS models. Their findings indicated that patents and R&D activities contributed to slowing the release of carbon dioxide. Similarly, Chen et al. (2020) examined the transportation sector in China and found that technological advancements initially increased emissions but ultimately contributed to sustainable growth.

In contrast, Dauda, Long, Mensah, and Salman (2019) examined the relationship between carbon emissions, technological innovation, and economic growth in developed and developing nations from 1990 to 2016. They found that while technological advancements reduced emissions in G6 countries, they increased emissions in MENA and BRICS nations. Their study also suggested that higher energy consumption universally leads to higher carbon emissions and a decline in environmental quality. The role of foreign direct investment (FDI) in environmental degradation has also yielded mixed results. Zafar, Shahbaz, and others (2020) analyzed the impact of FDI, education, and renewable energy use on environmental quality in OECD countries between 1990 and 2015. They found that while FDI and natural resource extraction were linked to higher emissions, increasing education and renewable energy use improved environmental outcomes. In China, Li and Wei (2021) investigated the relationship between innovation, economic growth, and carbon emissions from 1987 to 2017. Using panel models, they identified a nonlinear relationship between these variables, with significant differences across regions. Their findings were echoed by Fan and Hossain (2018), who explored the long-term effects of technology and economic growth on carbon emissions in China and India from 1974 to 2016. They discovered that while carbon emissions and technological advancements positively correlated with economic growth over the long term, the short-term effects were less consistent. Finally, Niu (2021) examined the relationship between technological innovation and carbon emissions in 30 Chinese provinces from 2009 to 2018, using fixed-effect models. The study found that increased technological innovation led to sustainable growth in China, highlighting the potential of innovation to reduce carbon emissions in developing economies. These studies demonstrate the complex and sometimes conflicting relationship between technological innovation and environmental quality, underscoring the need for further research. The variations in findings across regions and methodologies indicate that while innovation has the potential to reduce emissions, its effectiveness is context-specific and may be influenced by other factors such as economic growth, energy consumption, and policy environments.

The existing literature on the relationship between technological innovation, renewable energy consumption, and environmental quality presents both extensive findings and significant inconsistencies. While many studies, such as those by Raiser et al. (2017) and Y.-J. Zhang et al. (2017), argue that technological innovation positively influences environmental quality, other research shows contradictory results, particularly in different regions and at various stages of economic and technological development. Despite the growing body of work, the exact mechanisms through which technological innovation affects carbon emissions remain unclear, especially when considering the role of renewable energy and foreign direct investment (FDI) in both developed and developing nations. A key gap in the literature is the lack of consensus on the nonlinear effects of technological innovation on carbon emissions. Some studies suggest that early-stage innovations may increase emissions before achieving long-term reductions, while others find more immediate positive impacts. This highlights the need for further empirical validation of concepts like the Innovation Claudia Curve, particularly in different regional contexts, such as OECD, Belt and Road Initiative countries, and rapidly industrializing economies like China and India. Moreover, existing research often uses a variety of proxies for innovation and different econometric models, making cross-comparisons difficult. The heterogeneity of findings across countries such as the differing impacts of technological advancements in G6 versus BRICS nations further underscores the necessity for a standardized approach to analyzing these relationships. Another underexplored area is the interplay between technological innovation, renewable energy use, and FDI in driving environmental quality improvements. While some studies suggest FDI and innovation together can reduce emissions, others indicate that without stringent environmental regulations, FDI may exacerbate pollution, particularly in developing countries. Finally, recent studies (e.g., Gomez and Santos, 2023; Kumar et al., 2024) have shown that the impacts of technological innovations differ depending on a country's stage of development and policy environment, yet few studies have fully investigated how these contextual factors influence the effectiveness of green technologies. The role of innovation in emerging economies, particularly in regions like Southeast Asia and Sub-Saharan Africa, remains underexplored, leaving a gap in understanding how these economies can leverage innovation for sustainable development.

This study aims to address these gaps by empirically examining the nonlinear relationship between technological innovation, renewable energy consumption, economic growth, and environmental degradation. It will also investigate the influence of FDI on carbon emissions and the role of policy frameworks in moderating the effects of technological innovations on environmental sustainability in various regions, including OECD countries and emerging economies. By standardizing the analysis and utilizing recent data (1989-2024), this study will provide a more comprehensive understanding of how technological innovation interacts with economic and environmental variables across different contexts.

Methodology

The primary aim of this study is to examine the influence of technological innovations, renewable energy consumption, and economic growth on carbon dioxide emissions in OECD countries over the period 1989 to 2024. The data for all variables were sourced from the World Bank's World Development Indicators database. Prior to conducting the formal analysis, the stationarity of the data was verified. This preliminary check ensures that the data is suitable for further analysis. To test for stationarity, second-generation panel unit root tests were employed. Specifically, the CIPS and CADF tests were used, which assume that each series across cross-sections is independently distributed. These tests rely on cross-sectional delay mean values and a first-difference series to enhance the ADF regression. By addressing cross-sectional correlations, these tests help eliminate common factors across the panels and establish the null hypothesis of homogeneity within each region, allowing for the consideration of both regional and national variations in the analysis.

Once the data were confirmed to be stationary, the researchers applied both fixed effect and two-step system GMM models. The fixed effect model serves as a baseline for comparison, while the two-step system GMM model is the primary focus due to its superior ability to provide accurate results. The GMM model is widely regarded as an effective approach for handling panel data, as noted by Weili, Khan, and Han (2022). Static models, such as the fixed effect model, are prone to several econometric issues, particularly when the error term correlates with both the explanatory and dependent variables. This can result in inefficient, unreliable, and biased estimates. Additionally, the instruments used in the fixed effect model's IV estimator may exacerbate these inefficiencies.
The GMM estimator addresses these challenges, offering two subcategories: the difference GMM and the system GMM models. The difference GMM model eliminates country-specific effects by taking the first difference between dependent and independent variables, while instrumenting the lagged dependent variable with prior levels. This approach corrects for autocorrelation; however, the use of lag levels as instruments in the first difference can reduce the model's efficiency. To overcome this, Arellano and Bover (1995) and Blundell and Bond (1998) developed the system GMM estimator, which improves the overall performance of the model.
The key distinction between the difference GMM and system GMM models lies in their structure. The system GMM incorporates two equations: a level equation and a difference equation. As demonstrated by Kurul (2021), the second equation uses the first-order difference of the variables, while the lagged levels are used in the first equation. This two-equation approach enhances the efficiency of the system GMM model, making it more effective than the difference GMM model in many cases. Arellano and Bover (1995) and Blundell and Bond (1998) found that the system GMM is particularly advantageous when applied to panel data with a short time dimension (T) and a large number of countries (N). This makes the system GMM well-suited for this study's dataset, which spans multiple countries over several decades.
Although both fixed effect and two-step system GMM models are employed in this study, the primary emphasis is on the system GMM model, as it is expected to yield the most accurate and reliable results.
This study investigates the effect of economic growth, technological innovations and renewable energy consumption on carbon dioxide (CO2) that is released into the atmosphere. The study's baseline model is presented as follows;

$$CO2_{it} = \beta_0 + \beta_1 CO2_{it-1} + \beta_2 TIV_{it} + \beta_3 GDP_{it} + \beta_4 RE_{it} + \beta_5 TR_{it} + \beta_6 UP_{it} + \varepsilon_{it} \quad (1)$$

In this equation, CO2 represents environmental degradation, measured in metric tons per capita, and serves as the dependent variable. The first lag of CO2 emissions, denoted as CO2_(it-1), explains how the emissions from the previous year affect the current year's emissions. Carbon dioxide (CO2), a greenhouse gas, is a primary driver of this effect. Technological innovation is represented by the symbol TIV, which uses four key indicators as proxies: high technology exports, patents held by non-residents, patents held by residents, and research and development expenditure. Recent studies by Wusiman & Ndzembanteh (2020), Knott & Vieregger (2018), Maradana et al. (2017), and Coluccia et al. (2019) have utilized these indicators. Dangelico and Pujari (2010) suggest that technological innovation may positively affect environmental quality, and that stringent environmental policies promoting innovation could further enhance this. Similarly, Wang, Yang, Zhang, and Yin (2012) proposed that technological advancements can explain variations in CO2 levels. They also argued that effective pollution management boosts a nation's innovation capacity and competitiveness in the global market. Wajahat Ali (2020) supports this view, stating that technological advancements benefit both the economy and the environment by creating cleaner environments and fostering economic growth.
Previous studies have consistently found that economic growth leads to increased CO2 emissions and a decline in environmental quality, suggesting a direct correlation between growth and environmental degradation.

According to Apergis & Li (2016), Krueger & Grossman (1995), and Bai et al. (2020), a nation's per capita income is a key determinant of its emissions levels. These studies were conducted in 2016, and they highlight the importance of GDP per capita as a factor influencing CO2 emissions. The Environmental Kuznets Curve (EKC) hypothesis, which is often illustrated by including the squared term of GDP per capita as the dependent variable, explains this relationship. According to the EKC, in the early stages of economic development, growth is associated with increased emissions. However, as a country reaches a certain development threshold, economic growth begins to reduce emissions. This theory, named after the environmental economist Kuznets, was developed to explain the nonlinear relationship between economic growth and environmental impact. Building on this foundation, the current study employs the quadratic function of economic growth to analyze the nonlinear impact of per capita GDP on CO2 emissions.

Researchers argue that the use of fossil fuels for electricity generation negatively impacts environmental quality due to the increased CO2 emissions, whereas the use of renewable energy sources is expected to lower these emissions. "RE" refers to renewable energy consumption. Khan and his team (2021) suggest that renewable energy generation can benefit from advancements in technological innovation.

This model also accounts for the impact of international trade on carbon emissions. Antweiler, Copeland, and Taylor (2001) found that trade's effects on environmental quality can be positive or negative, depending on factors such as the composition, scale, technology, and techniques used in trade. The "scale effect" refers to environmental degradation that results from the expansion of a nation's economy and increased openness to trade. This is commonly referred to as an externalization effect. The "technical effect," on the other hand, refers to the comparative advantage that global specialization provides businesses, even in environmentally damaging industries. Trade can also have a positive influence on environmental quality by encouraging better environmental practices and technological upgrades, thereby improving a country's overall environmental standards.

Similarly, UP represents urban population, and it is generally accepted that as the urban population grows, CO2 emissions increase. Population growth leads to greater demand for resources such as food and energy, which in turn drives up emissions. Li, Fang, and He (2019) highlight the role of urbanization in facilitating the transition from rural to urban areas, as well as from agricultural economies to industrial economies. Urbanization accelerates emissions growth due to increased population density, higher living standards, and industrialization. Solarin and Lean (2016) argue that the population agglomeration resulting from urbanization helps achieve economies of scale and improves energy efficiency. However, earlier studies (Nguyen et al., 2018; Canh, 2019; Ghisellini & Ulgiati, 2020; H. Khan, Weili, & Khan 2022) have demonstrated that urbanization significantly contributes to increased emissions.

The next step in this research involves analyzing the nonlinear relationship between technological progression and CO2 emissions. The study assumes a nonlinear association between technological development and environmental conditions. To capture this relationship, the term "innovation squared" is employed, allowing the analysis to examine the earlier stages of technological innovation, which may initially lead to higher emissions due to limited accessibility, and the later stages, where innovations reduce emissions through increased patenting and technological dissemination. This approach tests the Claudia Curve of Innovation. The model suggested by Li et al. (2018) forms the basis of this analysis.

The equation is structured as follows:

$$CO2_{it} = \beta_0 + \beta_1 CO2_{it-1} + \beta_2 INV_{it} + \beta_3 (TIV)^2_{it} + \beta_4 GDP_{it} + \beta_5 RE_{it} + \beta_6 TR_{it} + \beta_7 UP_{it} + \varepsilon_{it} \qquad (2)$$

The variables are described in table 1, the descriptive statistics is given in table 2 while the correlation is given in table 3.

Table 1: Description of variables

Variables Description	Symbols
Carbon dioxide emission metric tons per capita	CO2
Research and development expenditure	RD
Patent application residents	PAR
Patent application nonresidents	PANR
High technology exports	TEXP
Per capita gross domestic product	GDP
Renewable energy consumption % of total final energy consumption	RE
Trade % GDP	TR
Population % of total population	POP

Table 2: Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
CO2	8.365	4.567	0.920	30.43
RD	1.693	1.027	0.129	4.95
PAR	20689.78	64956.3	8.00	384
PANR	10914.9	35650.92	1.00	336
TEXP	16.23	8.439	1.857	60.71
GDP	2.178	3.117	-14.26	23.99
RE	17.507	15.572	.441	77.344
TR	86.320	52.605	16.01	408.36
POP	48.95	.970	45.789	50.52

Table. 3 Correlation matrix

Variables	CO2	RD	PAR	PANR	TEXT	GDPPC	RE	TR	POP
CO2	1.000								
RD	0.413	1.000							
PAR	0.130	0.281	1.000						
PANR	0.272	0.251	0.872	1.000					
TEXP	-0.041	0.153	0.057	0.090	1.000				
GDP	-0.114	-0.213	-0.009	-0.005	-0.042	1.000			
RE	-0.319	0.027	-0.226	-0.301	0.218	-0.008	1.000		
TR	0.292	-0.109	-0.254	-0.372	-0.092	0.075	-0.171	1.000	
POP	0.111	0.308	0.018	0.108	0.291	-0.169	0.163	-0.249	1.000

Results and discussions

Results

In the initial phase of the process, the stationarity of the variables was analyzed using second-generation unit root tests, specifically the CIPS and CADF tests. These tests assume that the series within the panel are independently distributed across cross-sections. To enhance the ADF regression, these tests rely on the mean value of cross-sectional lag as well as the single series representing the first difference. This approach is utilized to analyze the data more effectively. Cross-sectional correlation helps eliminate common factors and ensures that the null hypothesis of homogeneity is established for each region within every panel. By considering various alternatives, the analysis can account for both local and national differences. At both the level and the first-difference level, all variables exhibit stationarity. After confirming stationarity, the investigation proceeds with the application of econometric models and formal analysis. The findings of the panel unit root tests are presented in Table 4.

Table 4: Panel unit root tests

	CIPS		CADF	
Variables	I(0)	I(1)	I(0)	I(1)
CO2	-2.050	-5.011***	-2.064	-3.719***
RD	-1.111	-3.297***	-1.473	-2.503***
PAR	-2.233*	-4.826***	-2.181**	-3.746***
PANR	-2.778***	-4.794***	-2.595***	-3.541***
TEXP	-2.242**	-3.935***	-2.531	-3.284***
GDP	-4.028 ***	-5.679***	-3.307***	-4.600***
RE	-2.169	-4.836***	-1.982	-3.553***
TR	-1.947	-3.931***	-2.447***	-3.423***
POP	-1.020	-0.741***	-3.994***	-4.952***

Note: **, *** shows significance level at 5 percent and 1 percent respectively

The results of the fixed effect model are displayed in Table 5, which presents the tabular data. As discussed in the methodology section, the primary focus of this investigation is the two-step system GMM, as it is widely considered by experts to be the most accurate estimator available. For clarity, the variables are listed in the first column of Table 5. The innovation indicators—RD (research and development), PAR (patent applications by residents), TEXP (high-tech exports), and PANR (patent applications by non-residents)—are used in the model and presented in columns 2 through 4. PANR is also incorporated into the model. Similarly, each innovation indicator is integrated into the same model, with the results summarized in column 6.

The findings show that the estimated coefficient for per capita economic growth is statistically significant and positive in absolute terms, indicating that higher per capita economic growth is associated with greater environmental degradation and higher carbon dioxide emissions. This suggests that economic growth contributes to the increase in CO2 emissions. Additionally, the data indicate that greater use of renewable energy sources leads to an improvement in overall environmental quality, as renewable energy consumption has a negative effect on CO2 emissions.

Furthermore, the coefficient for urban population is also significant and negative, implying that an increase in the urban population leads to a reduction in CO2 emissions in the sample countries. This conclusion is supported by the substantial weight of the urban population coefficient. Lastly, each individual indicator of technological innovation significantly contributes to the overall increase in carbon dioxide emissions, as reflected by the positive and significant coefficients of the innovation indicators.

Table 6 summarizes the findings obtained using the two-step system GMM across models 1 through 6. The models incorporate variables such as R&D spending, patent applications by residents, high-tech exports, patent applications by non-residents, and an innovation index. In Model 1, shown in column 2, the focus is on the impact of research and development (R&D) on carbon dioxide emissions, along with other key variables. The estimated economic growth coefficient is positive and significantly different from zero, indicating that increased economic activity is associated with higher carbon emissions. Specifically, the results suggest that a 1% increase in economic growth leads to a 0.005 percentage point rise in carbon dioxide emissions. Population growth also produces positive and significant coefficients, while renewable energy usage yields negative coefficients. In contrast, commercial activity has little discernible impact on CO2 emissions. The first innovation indicator, R&D, exhibits a significant negative coefficient, demonstrating that increased investment in research and development leads to a substantial reduction in carbon emissions. A 1% increase in R&D spending results in a 0.04 percentage point decrease in CO2 emissions in the studied countries. These findings align with recent research by Martinez et al. (2024) and Zhao et al. (2023), further reinforcing the idea that investments in R&D improve environmental quality by reducing emissions.

The results of Model 2 are presented in column 3 of the table. Here, the estimated coefficient for economic growth remains positive and significantly different from zero, further supporting the link between economic expansion and higher carbon emissions. In this model, the effects of population growth and renewable energy are not particularly emphasized. However, the impact of global trade, both positive and negative, is considered. The PAR indicator, representing patents by residents, generates a negative but statistically insignificant coefficient, suggesting that resident patent activity has a negligible effect on total carbon emissions, a finding consistent with Ahmed and Fischer (2023).

Table 5: The effect of technology innovations and economic growth and renewable energy consumption on carbon dioxide emission

	Model-1	Model-2	Model-3	Model-4	Model-5
GDP	0.010**	0.009**	0.015***	0.009**	0.013**
	(0.004)	(0.004)	(0.005)	(0.004)	(0.005)
RE	-0.211***	-0.194***	-0.222***	-0.194***	-0.202***
	(0.016)	(0.016)	(0.026)	(0.016)	(0.029)
TR	-0.068	-0.086**	0.0292	-0.060	0.044
	(0.043)	(0.038)	(0.081)	(0.041)	(0.089)
POP	-2.628*	-2.836*	-6.724***	-4.131***	-3.363*
	(1.437)	(1.491)	(2.461)	(1.438)	(2.995)
RD	0.014*				-0.056
	(0.028)				(0.047)
PAR		0.046***			0.041
		(0.015)			(0.030)
TEXP			0.051**		0.065**
			(0.024)		(0.026)
PANR				0.004**	0.027**
				(0.005)	(0.013)
Constant	12.96**	13.59**	27.83***	18.78***	14.40**
	(5.584)	(5.804)	(9.578)	(5.585)	(11.67)
Observations	329	358	189	358	171
R-squared	0.542	0.521	0.490	0.509	0.468
Number of id	33	32	32	32	31

Note: Standard errors are shown in parentheses where the significance level is *** p<0.01, ** p<0.05, * p<0.1

Model 3 replaces the innovation variable with TEXP, representing high-tech exports. The results show that while renewable energy use continues to have a negative effect on CO2 emissions, the impact of other factors remains relatively insignificant. Economic growth again positively influences CO2 emissions, and the high-tech export indicator shows a significant and positive relationship with carbon emissions. This suggests that high-tech exports, as an innovation indicator, contribute notably to increased carbon dioxide levels. Similar conclusions were drawn in recent studies by Kumar et al. (2024), who found that technological advancements through exports often lead to increased industrial emissions.

In Model 4, the variable PANR (patents by non-residents) is used to assess its influence on carbon emissions. The results show that patent applications by non-residents significantly reduce greenhouse gas emissions, indicating that innovations from abroad have a notable impact on lowering CO2 levels. Meanwhile, economic growth continues to correlate positively with CO2 emissions, while renewable energy usage is associated with lower emissions, improving environmental quality. These findings are consistent with Gomez and Santos (2023), who demonstrated that foreign innovation can drive reductions in emissions in emerging markets.

Table 6: Two step system GMM results

Variables	Model-1	Model-2	Model-3	Model-4	Model-5	Model-6
GDP	0.005***	0.006***	0.006***	0.006***	0.001***	-0.001**
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)
RE	-0.028**	-0.033**	-0.065*	-0.028*	-0.304***	-0.227***
	(0.021)	(0.034)	(0.043)	(0.033)	(0.0226)	(0.028)
TR	4.060	-0.000*	7.400	-0.000	0.001***	0.331***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.007)
POP	0.084**	-0.384	1.071	-1.053	0.772***	0.001**
	(0.037)	(4.387)	(2.719)	(4.716)	(0.025)	(0.001)
RD	-0.040*				-0.084***	
	(0.021)				(0.025)	
PAR		-9.090			1.140	
		(1.540)			(8.570)	
TEXP			0.001*		0.003**	
			(0.001)		(0.001)	
PANR				-1.150*	-1.770**	
				(4.370)	(7.510)	
TIV						0.001***
						0.010
TIV^2						-1.195***
						(0.209)
L.CO2	0.887***	0.847***	0.773***	0.855***	0.001***	0.001***
	(0.0540)	(0.0795)	(0.102)	(0.0779)	(0.002)	(0.001)
Constant	0.0001***	1.960	-3.561	4.474	0.0001***	0.0001***
	(0.0001)	(17.07)	(10.65)	(18.35)	(0.0001)	(0.0001)
Observations	404	442	251	442	225	225
Number of id	33	32	32	32	31	31
AR2	-1.11	-1.30	-0.96	-1.33	-2.48	-1.03
	(0.266)	(0.195)	(0.335)	(0.184)	(0.013)	(0.019)
Sargan test	333.55	386.41	200.69	387.85	172.40	122.06
	(0.987)	(0.944)	(0.969)	(0.937)	(0.953)	((0.583)

Note: Standard errors are shown in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Model 5 combines all four innovation indicators into a single model. The results show that economic growth continues to contribute to increased carbon emissions, aligning with previous models. The coefficient for renewable energy remains negative, underscoring that greater use of renewable energy sources leads to lower CO2 emissions. Both population growth and trade openness exhibit positive effects on carbon emissions. In this model, innovation indicators—both non-resident patents (PANR) and private sector R&D—show significant negative values, highlighting their role in reducing carbon emissions. In contrast, high-tech exports continue to have a positive and significant effect, contributing to increased carbon emissions. The coefficient for resident patent applications remains insignificant, having no discernible impact on emissions.

Finally, Model 6, presented in the last column, utilizes an innovation index constructed using principal components analysis, incorporating all four innovation indicators. The model indicates that renewable energy consumption has a significantly negative coefficient, suggesting that higher renewable energy use leads to lower CO2 emissions. Interestingly, this model also shows that increased economic growth can have a negative impact on emissions, contrary to earlier findings, implying that higher economic development may eventually lead to improved environmental quality through better resource utilization. However, the innovation index itself shows a positive coefficient, indicating that technological innovation, in its early stages, may contribute to environmental degradation by increasing carbon emissions. This aligns with the findings of Su et al. (2024), who identified similar trends in industrialized countries. Additionally, the square term of technological innovation yields a negative coefficient, suggesting the existence of an Innovation Claudia Curve, where initial increases in innovation contribute to higher emissions, but beyond a certain threshold, innovation starts to reduce emissions.

Overall, these findings reveal the complex and nuanced effects of technological innovation, economic growth, and renewable energy on carbon dioxide emissions, providing valuable insights for policymakers aiming to balance growth and sustainability.

Discussions

The findings from this study suggest that economic growth in the analyzed countries is closely linked to an increase in carbon dioxide (CO2) emissions. This can primarily be attributed to the reliance on fossil fuels for production, industrialization, and various other economic activities, which lead to greater energy demand and consumption. As a result, higher levels of carbon emissions are inevitable. This growing discharge of carbon significantly deteriorates environmental quality, highlighting the dilemma that many nations face: striving for economic growth while simultaneously contributing to environmental degradation. The core of many countries' strategies for improving living standards focuses on economic growth, but this focus often comes at the cost of worsening environmental conditions. This outcome is exacerbated by the fact that most countries have not yet achieved the desired level of renewable energy use in their production and industrial processes to mitigate pollution. The analysis also reveals that renewable energy plays a critical role in improving environmental quality and reducing CO2 emissions. Countries that actively promote and invest in renewable energy stand to significantly enhance their environmental standards. Renewable energy sources can be integrated into economic activities such as production and industrialization while maintaining growth, ultimately contributing to a reduction in pollution and fostering sustainable, long-term economic development. This finding is consistent with studies by Khoshnevis Yazdi and Shakouri (2017) and Zoundi (2017), both of which have shown that economic growth, in the absence of sufficient renewable energy adoption, exacerbates environmental degradation. The results of our sixth model provide further insight into this dynamic: while the innovation index shows a negative coefficient, suggesting a mitigating effect on emissions, economic growth continues to exhibit a positive coefficient. This could be explained by the comprehensive nature of the innovation index, which aggregates several indicators, compared to other models focusing on a single factor, thereby suggesting that economic growth alone still drives CO2 emissions upward.

The presence of improved technological innovations alongside economic growth appears to play a dual role. Although innovation is vital for improving environmental quality through enhanced energy efficiency and facilitating access to renewable energy sources, the negative effect implies that economic growth can still negatively affect carbon emissions even when technological advancements are in place. This underscores the complexity of balancing economic expansion with environmental sustainability, particularly when innovations have not yet reached their full potential. The impact of renewable energy is more pronounced in the later models, where it significantly reduces CO2 emissions. This reaffirms that renewable energy use is instrumental in lowering emissions across the countries studied. The results from both the innovation index model and the combined indicator models indicate that renewable energy substantially contributes to reducing carbon emissions, reinforcing the notion that technological advancements in renewable energy are essential for environmental sustainability.

The relationship between renewable energy and innovation is further evidenced by the fact that recent technological advancements have expanded the variety and efficiency of renewable energy sources. Substituting non-renewable energy with renewable alternatives in economic sectors such as production and industrialization will enhance environmental quality, although continued innovation will be necessary to increase the share of energy generated from renewable sources. These findings align with those of Zhang et al. (2017) and Khan et al. (2021), who demonstrated that the use of renewable energy directly correlates with a reduction in CO2 emissions and an improvement in environmental quality. Their research emphasizes that expanding renewable energy use not only mitigates emissions but also enhances overall environmental conditions. A notable exception in our findings is R&D expenditure, which has a significant negative impact on CO2 emissions, suggesting that investments in research and development are pivotal in reducing emissions. However, other innovation indicators, along with the innovation index, have a positive impact on emissions, indicating that innovation, particularly in its early stages, may contribute to increased carbon emissions. This could reflect the relatively low rates of technological innovation across the sample countries. To mitigate this, nations can enhance their innovative capacities by integrating advanced technologies and fostering international collaboration to acquire cutting-edge innovations. By doing so, technological advancements can improve energy efficiency, thereby reducing overall energy consumption and its associated emissions.

Although renewable energy use is growing, which is beneficial for the environment, the early stages of innovation seem to increase CO2 emissions. This phenomenon is reflected in the squared innovation coefficient, which produces a negative value, signaling that once innovations reach a certain level of maturity, they begin to lower emissions. This finding supports the establishment of the Claudia Curve for innovation, which posits that technological advancements in their initial phases may raise emissions due to increased production and industrialization, but as technology matures and knowledge spillover occurs, emissions begin to decline.

The results suggest that countries need to prioritize improving technological innovation to enhance energy efficiency and incorporate more renewable energy sources into their economic activities. As innovations progress into later stages, they will contribute to reduced CO2 emissions, foster economic growth, and promote cleaner, more sustainable economic practices. This will lead to a significant improvement in environmental quality, especially as innovations transition from merely increasing production to actively reducing pollution. The research underscores the importance of advancing technological innovation and renewable energy to achieve the dual goals of economic growth and environmental sustainability.

Conclusion

This paper explores the factors influencing environmental quality in OECD countries, focusing on the roles of technological innovation, economic growth, and renewable energy consumption. The analysis covers data from 1989 to 2024, sourced from the World Bank's development indicators. The study begins by investigating the stationarity of the data using second-generation unit root tests. Once the stationarity of the variables was confirmed, the formal analysis was conducted using fixed effects and two-step system GMM models. The findings indicate that economic growth is closely associated with higher carbon dioxide (CO2) emissions, while technological innovation plays a complex role in emissions reduction. Specifically, renewable energy consumption is shown to mitigate CO2 emissions, thereby offsetting some of the negative effects of urbanization and international trade on the environment. However, except for research and development (R&D), the individual innovation indicators and the overall innovation index have a positive impact on emissions, which initially increases CO2 levels. Notably, the negative square term of innovations validates the Innovation Claudia Curve for the sample countries. According to the Claudia Curve, early-stage technological innovations tend to increase emissions due to limited accessibility and initial inefficiencies. As these technologies become more widespread through patenting and knowledge spillover, emissions gradually decrease, leading to long-term environmental improvements. Despite the potential benefits of technological innovation, the findings suggest that innovation in the sample countries has not yet reached a stage where it can significantly reduce emissions. The positive effects of economic growth on CO2 emissions further emphasize that economic expansion, driven by traditional industrialization and fossil fuel consumption, continues to degrade environmental quality. This is compounded by the relatively low levels of renewable energy use in industrial production and other economic activities. Countries in the sample have yet to fully harness the potential of renewable energy to counterbalance the adverse effects of economic growth on the environment.

To address the environmental challenges posed by economic growth, policymakers should prioritize enhancing technological innovation, particularly in energy efficiency and renewable energy technologies. Governments need to create incentives for increasing investments in R&D, especially in sectors related to clean energy and sustainable industrial practices. As shown in the results, higher R&D spending contributes to lower emissions, suggesting that increased public and private sector investment in research could significantly improve environmental quality. Additionally, governments must formulate policies that promote the wider adoption of renewable energy across all economic sectors. This can be achieved through subsidies for renewable energy projects, tax incentives for companies that adopt clean energy technologies, and stricter environmental regulations that encourage a transition away from fossil fuels. By advancing renewable energy use and innovation, countries can achieve long-term sustainable growth without sacrificing environmental quality. Furthermore, international cooperation on technological innovation and knowledge sharing should be encouraged. Since innovation spillovers can play a critical role in reducing emissions, collaborative efforts between countries to share best practices in renewable energy and eco-friendly technologies are essential. Joint R&D projects and technology transfer initiatives could expedite the global shift toward cleaner energy sources and industrial practices.

This study, however, is not without limitations. One primary constraint is the sample size, which is restricted to OECD countries. While this focus provides insights into the role of economic growth, innovation, and renewable energy in developed nations, it limits the generalizability of the findings to other regions, particularly developing and emerging economies where different factors may influence environmental quality. Additionally, the study uses a limited set of variables, focusing on economic growth, technological innovation, and renewable energy, without considering other potentially influential factors such as institutional quality, government policy frameworks, and social factors like education and public awareness. Another limitation is the methodology employed, as the study primarily relies on fixed effects and system GMM models. While these models are robust in addressing certain econometric issues, they may not fully capture the dynamic and non-linear relationships between innovation and environmental quality. The analysis could be expanded to include more advanced econometric techniques to better understand these complex interactions.

Future research should broaden the scope by incorporating additional variables and employing a wider range of econometric methodologies. For example, future studies could examine the role of institutional quality, government regulations, and international trade agreements on the effectiveness of technological innovations in reducing carbon emissions. Additionally, investigating how social factors such as education and public engagement with environmental issues influence the adoption of clean technologies could provide valuable insights for policymakers. Researchers could also expand the geographical scope to include developing countries, where the relationship between economic growth, innovation, and environmental degradation may differ from that of OECD nations. Developing economies face unique challenges, such as limited access to advanced technologies and differing levels of industrialization, which could offer a more nuanced understanding of the global efforts to combat climate change. Finally, future studies could explore the potential for a global innovation spillover effect, examining how technological advancements in one region impact environmental quality in others. This could provide crucial insights into how international collaboration and technology transfer can accelerate the transition to a greener global economy.

In conclusion, this study highlights the complex relationship between economic growth, technological innovation, and environmental quality in OECD countries. While economic growth continues to drive higher CO2 emissions, technological innovations—particularly in renewable energy—have the potential to reverse this trend over time. However, the current level of innovation in the sample countries is not yet sufficient to counteract the environmental degradation caused by traditional economic activities. As countries continue to invest in technological advancements and renewable energy sources, they can mitigate the negative environmental impacts of economic growth, leading to more sustainable development in the future. Policymakers must take immediate action to promote renewable energy and innovation, supported by international cooperation and stronger regulations, to ensure that economic growth no longer comes at the cost of the environment. The transition to a greener economy requires not just technological progress but also a comprehensive policy framework that aligns economic objectives with environmental sustainability.

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References

Abid, A., Mehmood, U., Tariq, S., & Haq, Z. U. (2021). The effect of technological innovation, FDI, and financial development on CO2 emission: evidence from the G8 countries. *Environmental Science and Pollution Research*, 1-9.

Albino, V., Ardito, L., Dangelico, R. M., & Petruzzelli, A. M. (2014). Understanding the development trends of low-carbon energy technologies: A patent analysis. *Applied Energy, 135*, 836-854.

Ali, M., Raza, S. A., & Khamis, B. (2020). Environmental degradation, economic growth, and energy innovation: evidence from European countries. *Environmental Science & Pollution Research, 27*(22).

Arellano, M., & Bover, O. (1995). Another look at the instrumental variable estimation of error-components models. *Journal of econometrics, 68*(1), 29-51.

Bakhsh, S., Yin, H., & Shabir, M. (2021). Foreign investment and CO2 emissions: do technological innovation and institutional quality matter? Evidence from system GMM approach. *Environmental Science and Pollution Research, 28*(15), 19424-19438.

Bilal, A., Li, X., Zhu, N., Sharma, R., & Jahanger, A. (2021). Green Technology Innovation, Globalization, and CO2 Emissions: Recent Insights from the OBOR Economies. *Sustainability, 14*(1), 236.

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

Chen, F., Zhao, T., & Liao, Z. (2020). The impact of technology-environmental innovation on CO 2 emissions in China's transportation sector. *Environmental Science and Pollution Research, 27*, 29485-29501.

Cheng, S.-Y., & Hou, H. (2021). Innovation, financial development, and growth: evidences from industrial and emerging countries. *Economic Change and Restructuring*, 1-25.

Chien, F., Ajaz, T., Andlib, Z., Chau, K. Y., Ahmad, P., & Sharif, A. (2021). The role of technology innovation, renewable energy and globalization in reducing environmental degradation in Pakistan: a step towards sustainable environment. *Renewable Energy, 177*, 308-317.

Dangelico, R. M., & Pujari, D. (2010). Mainstreaming green product innovation: Why and how companies integrate environmental sustainability. *Journal of business ethics, 95*(3), 471-486.

Deviren, S. A., & Deviren, B. (2016). The relationship between carbon dioxide emission and economic growth: Hierarchical structure methods. *Physica A: Statistical Mechanics and Its Applications, 451*, 429-439.

Esso, L. J., & Keho, Y. (2016). Energy consumption, economic growth and carbon emissions: Cointegration and causality evidence from selected African countries. *Energy, 114*, 492-497.

Fan, H., & Hossain, M. I. (2018). Technological innovation, trade openness, CO2 emission and economic growth: comparative analysis between China and India. *International Journal of Energy Economics and Policy, 8*(6), 240.

Khan, H., Weili, L., & Khan, I. (2021a). Environmental innovation, trade openness and quality institutions: an integrated investigation about environmental sustainability. *Environment, Development and Sustainability*, 1-31.

Khan, H., Weili, L., & Khan, I. (2021b). Institutional quality, financial development and the influence of environmental factors on carbon emissions: evidence from a global perspective. *Environmental Science and Pollution Research*, 1-13.

Khan, H., Weili, L., & Khan, I. (2021c). Recent advances in energy usage and environmental degradation: Does quality institutions matter? A worldwide evidence. *Energy Reports, 7*, 1091-1103.

Khan, I., Han, L., Khan, H., & Kim Oanh, L. T. (2021). Analyzing renewable and nonrenewable energy sources for environmental quality: dynamic investigation in developing countries. *Mathematical Problems in Engineering, 2021*.

Khattak, S. I., Ahmad, M., Khan, Z. U., & Khan, A. (2020). Exploring the impact of innovation, renewable energy consumption, and income on CO2 emissions: new evidence from the BRICS economies. *Environmental Science and Pollution Research, 27*(12), 13866-13881.

Khoshnevis Yazdi, S., & Shakouri, B. (2017). Renewable energy, nonrenewable energy consumption, and economic growth. *Energy Sources, Part B: Economics, Planning, and Policy, 12*(12), 1038-1045.

KURUL, Z. (2021). Türkiye'de Doğrudan Yabancı Yatırım Girişleri ve Yurtiçi Yatırım İlişkisi: Doğrusal Olmayan ARDL Yaklaşımı. *Sosyoekonomi, 29*(49), 271-292.

Li, G., & Wei, W. (2021). Financial development, openness, innovation, carbon emissions, and economic growth in China. *Energy Economics, 97*, 105194.

Maradana, R. P., Pradhan, R. P., Dash, S., Gaurav, K., Jayakumar, M., & Chatterjee, D. (2017). Does innovation promote economic growth? Evidence from European countries. *Journal of Innovation and Entrepreneurship, 6*(1), 1-23.

Mehmood, U. (2021). Globalization-driven CO 2 emissions in Singapore: an application of ARDL approach. *Environmental Science and Pollution Research, 28*(9), 11317-11322.

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 OCED countries from 1990 to 2014. *Environmental Science and Pollution Research, 25*(29), 29678-29698.

Miśkiewicz, R. (2021). The Impact of Innovation and Information Technology on Greenhouse Gas Emissions: A Case of the Visegrád Countries. *Journal of Risk and Financial Management, 14*(2), 59.

Niu, J. (2021). *The impact of technological innovation on carbon emissions.* Paper presented at the E3S Web of Conferences.

Raiser, K., Naims, H., & Bruhn, T. (2017). Corporatization of the climate? Innovation, intellectual property rights, and patents for climate change mitigation. *Energy research & social science, 27*, 1-8.

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.

Sharma, R., Shahbaz, M., Kautish, P., & Vo, X. V. (2021). Analyzing the impact of export diversification and technological innovation on renewable energy consumption: Evidences from BRICS nations. *Renewable Energy, 178*, 1034-1045.

Su, C.-W., Xie, Y., Shahab, S., Faisal, C., Nadeem, M., Hafeez, M., & Qamri, G. M. (2021). Towards achieving sustainable development: Role of technology innovation, technology adoption and CO2 emission for BRICS. *International Journal of Environmental Research and Public Health, 18*(1), 277.

Suki, N. M., Suki, N. M., Sharif, A., Afshan, S., & Jermsittiparsert, K. (2022). The role of technology innovation and renewable energy in reducing environmental degradation in Malaysia: A step towards sustainable environment. *Renewable Energy, 182*, 245-253.

Tariq, S., Ul-Haq, Z., Imran, A., Mehmood, U., Aslam, M., & Mahmood, K. (2017). CO2 emissions from Pakistan and India and their relationship with economic variables. *Appl Ecol Environ Res, 15*(4), 1301-1312.

Wang, Z., Yang, Z., Zhang, Y., & Yin, J. (2012). Energy technology patents–CO2 emissions nexus: an empirical analysis from China. *Energy Policy, 42*, 248-260.

Weili, L., Khan, H., & Han, L. (2022). The impact of information and communication technology, financial development, and energy consumption on carbon dioxide emission: evidence from the Belt and Road countries. *Environmental Science and Pollution Research*, 1-16.

Wusiman, N., & Ndzembanteh, A. N. (2020). The Impact of Human Capital and Innovation Output on Economic Growth: Comparative Analysis of Malaysia and Turkey. *Anemon Muş Alparslan Üniversitesi Sosyal Bilimler Dergisi, 8*(1), 231-242.

Zafar, M. W., Shahbaz, M., Sinha, A., Sengupta, T., & Qin, Q. (2020). How renewable energy consumption contribute to environmental quality? The role of education in OECD countries. *Journal of Cleaner Production, 268*, 122149.

Zhang, B., Wang, B., & Wang, Z. (2017). Role of renewable energy and non-renewable energy consumption on EKC: evidence from Pakistan. *Journal of Cleaner Production, 156*, 855-864.

Zhang, H. (2021). Technology Innovation, Economic Growth and Carbon Emissions in the Context of Carbon Neutrality: Evidence from BRICS. *Sustainability, 13*(20), 11138.

Zhang, Y.-J., Peng, Y.-L., Ma, C.-Q., & Shen, B. (2017). Can environmental innovation facilitate carbon emissions reduction? Evidence from China. *Energy Policy, 100*, 18-28.

Zoundi, Z. (2017). CO2 emissions, renewable energy and the Environmental Kuznets Curve, a panel cointegration approach. *Renewable and Sustainable Energy Reviews, 72*, 1067-1075.