The Green Technological Innovation-Renewable Energy-Carbon Nexus in the Big Four Emerging Economies: Evidence from Fixed-Effects Model with Driscoll–Kraay Standard Errors

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Abstract

This study aims to investigate the relationships among green technological innovation (GTI), renewable energy consumption (REC), and economic growth and carbon emissions in China, Russia, Brazil, and India, using panel data from 2001 to 2024. To address cross-sectional dependence and heterogeneity, a fixed-effects model with Driscoll-Kraay standard errors is employed. The findings show that renewable energy consumption significantly reduces carbon emissions in these economies, while GTI, economic growth, and trade openness are positively linked with CO2 emissions. Thus, the outcomes show that current technological innovations may still be closely connected to carbon-intensive industrial activities. These outcomes suggest that increasing the adoption of renewable energy sources and shifting innovation priorities toward clean technologies are essential to support sustainable development and achieve significant reductions in carbon emissions in emerging economies.

Keywords: Emerging Economies; Green Technological Innovation; CO_2 Emissions; Renewable Energy Consumption.

Introduction

The 21st century has been characterised by increasing environmental degradation and worsening climate change, largely driven by rising CO2 emissions. Industrialisation, reliance on fossil fuels, increased trade (Ikram & Gul, 2024), and rising energy demand have placed significant environmental strain on both developed and developing economies (Su et al., 2020). Nations are increasingly being forced to harmonise their energy resources with socially fair and environmentally friendly technologies to reduce negative environmental effects (Safdar et al., 2022; Umar et al., 2020a; Umar et al., 2020b). Achieving carbon neutrality is a primary focus of international policy, as it's crucial to decouple GDP growth from carbon-intensive energy sources, given the ongoing reliance on fossil fuels. The GTI has become a key mechanism for achieving sustainable development and minimising environmental harm (Umar et al., 2021a).

Green technological innovation has emerged as a significant contributor to eco-economic development (Luo et al., 2019), promoting sustainable development and reducing environmental

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externalities, thereby distinguishing it from traditional growth paradigms (Lin et al., 2018; Wu et al., 2020; Wu et al., 2021). When it was first initiated, its concept emerged from environmentally sound technologies (ESTs) focused on pollution reduction, environmental cleanup, recycling, and environmental monitoring (Braun & Wield, 1994; Verhoosel, 1998; Safdar et al., 2026). Green innovation has, over the years, developed into a multifaceted system of sustainability that integrates environmental safety, technological advancement, and structural economic change (Guo et al., 2018; Guo et al., 2020). In response to global environmental demands, governments are increasingly supportive of GI and REC, providing financial incentives and institutional policies (Jamal et al., 2024; Wang et al. 2021). Though RNE is another significant part of the move to a low-carbon economy. The main renewable energy sources, such as Solar, wind, biomass, and hydropower, play a key role in reducing environmental pollution, improving energy security, and mitigating climate risks (Shahid et al., 2025; Tareen et al., 2018; Gielen et al., 2019). A large body of empirical research supports an indirect association between REC and CO2 emissions. Moreover, GTI and the development of renewable energy often go hand in hand, with innovative technologies improving the efficiency of energy consumption and enabling the wider promotion of renewable technologies (Bilgili et al. 2016; Heal, 2010; Shahzad et al. 2017). The ability of renewable energy to enhance environmental quality, therefore, depends on the development of green innovation (Ullah et al., 2023; Muhammad et al., 2023; Shah et al., 2020; Wu et al., 2020).

Emerging economies play a key role in global climate change. Among them are Brazil, Russia, India, and China, commonly known as the Big Four Emerging Economies, which contribute a remarkably large share of global output, energy use, and CO2 emissions. These economies face many challenges: maintaining high growth rates while reducing environmental degradation (Riaz et al., 2024; Fatima et al., 2023). Even though recent literature has studied the roles of GTI and renewable energy consumption in emerging economies, there are very few studies exploring the nexus among GTI, renewable energy consumption, and CO2 emissions in the Big Four economies, employing advanced techniques to address CSD and heterogeneity, a Fixed-Effect model with Driscoll-Kraay standard error model. Against this background, the current study aims to examine the impacts of green technological innovation, renewable energy consumption, economic growth, and trade openness on CO2 emissions in the Big Four Emerging nations (Bilgili et al. 2016; Heal, 2010; Shahzad et al. 2017; Iqbal & Safdar, 2024).

Although the literature on green technological innovation and renewable energy is expanding, several gaps remain. First, most studies focus on individual countries with limited attention to the Big Four Emerging Economies. These are the largest contributors to global emissions and energy markets. Second, research usually examines REC and GTI separately. Few incorporate GTI, renewable energy consumption, GDP, and trade openness within a single empirical framework. Third, many studies rely on estimation techniques such as ARDL, FMOLS, or DOLS. These may not fully account for CSD, heteroscedasticity, and serial correlation. This paper addresses these gaps by using a Fixed Effects model with Driscoll-Kraay standard errors for stronger inference on the big four emerging Economies.

Study Hypothesis

The current study formulates the following hypothesis:

H1: Green technological innovation significantly affects CO2 emissions.

H2: Renewable energy consumption significantly diminishes CO2 emissions in the Big-4 Emerging countries.

The remainder of this paper is prepared as follows: the literature review is presented in Section 2. Section 3 displays the methodology and data source. Section 4 presents empirical findings and their interpretation. Finally, Section 5 provides the conclusion and policy recommendations.
Green technology innovation has emerged as a major driver of the world's transition to low-carbon development, particularly in emerging economies, where rapid industrialisation and heavy reliance on fossil fuels put pressure on the environment. Initially, the discussion of eco-friendly technologies focused on reducing pollution, recycling, environmental surveillance, and environmentally friendly production systems as means to alleviate ecological degradation (Braun & Wield, 1994; Verhoosel, 1998). Over time, green innovation has come to be viewed as a broader concept of sustainability that uses resources more efficiently, is cleaner in its processes, and is less damaging to the environment (Gul et al., 2026; Guo et al., 2020). In support of this broader view, empirical evidence collected over a significant period has indicated that innovation-based solutions, such as GTI and R&D funds, contribute to reduced CO2 emissions by enhancing energy efficiency and enabling shifts to cleaner production methods (Lin et al., 2018; Wu et al., 2020; Wu et al., 2021). Thus, technological development is seen to help decouple economic growth from carbon-intensive energy systems and contribute to achieving carbon neutrality (Umar et al., 2020b; Su et al., 2020). However, some literature presents a contrasting perspective. In emerging economies, innovation can initially drive the growth of industrial scale and energy consumption, leading to higher emissions—particularly in the context of technological advancement within carbon-intensive industries or in environments where environmental regulation is ineffective (Grossman and Krueger, 1995; Heal, 2010). This ambiguous evidence suggests that the environmental effects of innovation depend on both structural orientation and policy context. Based on the theoretical perspective that GTI improves CO2 emissions, the following hypothesis is formulated:
H1: Green technological innovation significantly affects CO_2 emissions.

Another important pillar of mitigating climate change is the adoption of RE, which decreases dependence on fossil fuels and promotes environmental sustainability (Tareen et al., 2018). Solar, wind, biomass, and hydropower are considered renewable energy sources capable of reducing emissions intensity and strengthening energy security (Gielen et al., 2019). Studied by Shah et al. (2020) and Bilgili et al. (2016) found that renewable energy sources have a negative connection with the CO2 emissions, meaning that the higher the degree to which people use renewable sources, the more the environmental pressures are mitigated through the promotion of the consumption of cleaner electricity and other alternative sources. However, the environmental benefits of RECs depended on several supporting provisions, such as technological development, effective system operation, and proper infrastructure. According to Heal (2010) and Shahzad et al. (2017), renewable energy's ability to reduce emissions might be limited when innovation capacity is constrained or the energy transmission system is inefficient. These reflections clarify the necessity of considering renewable energy and technological advancement simultaneously in assessing ways to improve low-carbon perspectives. Based on this, the second hypothesis is the following:
H2: Renewable energy consumption significantly reduces CO_2 emissions

Research Methodology

Theoretical Framework

This study is based on sustainable development and the Environmental Kuznets Curve (EKC) hypothesis. Sustainable development focuses on improving the association among GDP growth, environmental management, and technological innovation, and ensuring long-term ecological balance. Green technological innovation (GTI) is viewed as a critical instrument of improving the process of environmental degradation and maintaining an ongoing economic growth within this paradigm (Wu et al., 2021). GTI encourages greater energy efficiency, pollution reduction, and cleaner production, which can help reduce the connection between economic growth and CO2 emissions (Umar et al., 2020a). The EKC hypothesis proposes that environmental decline mostly rises with economic development but levels off at a specified income level (Grossman and Krueger, 1995). The RCE plays a critical role in reducing CO2 emissions and improving environmental quality. However, the environmental effectiveness of REC depends on the level of technological advancement and the capability to modernise (Heal, 2010). As a result, the intersection of GTI and REC is predicted to influence environmental conditions in emerging economies.

Data and Variables

In the current study, we used a panel dataset of the 4 emerging economies from 2001 to 2024. The group of economies included in this study comprises Brazil, China, Russia, and India; data for all countries were collected from WDI. Note: Table 1 provides variable descriptions; Figure 1 shows the standardisation of the variables.

Figure 1: Standardization of the variables

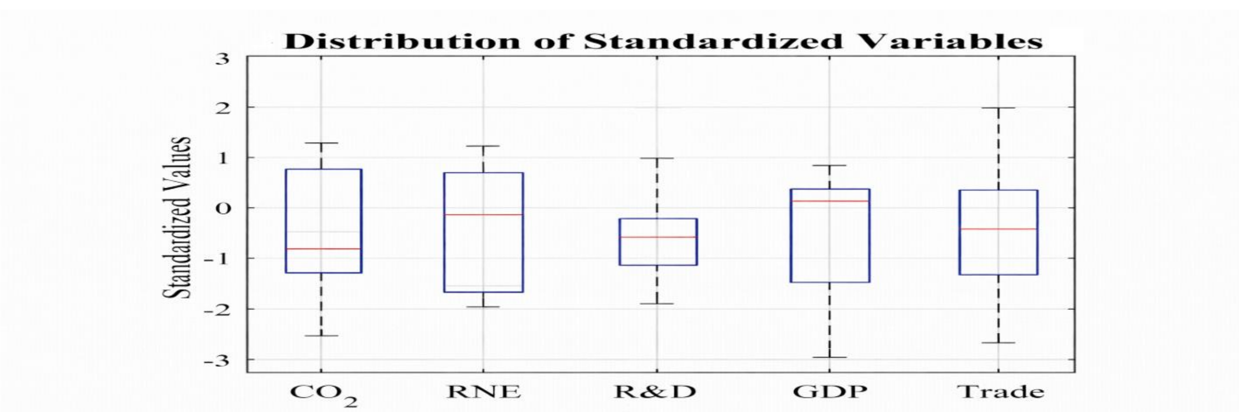


Table 1: Variable Description

Variable	Definition	Measurement	Source
CO2	CO2 emissions per capita	CO2 per capita (metric tons)	WDI
RNE	Renewable energy consumption	% of total final energy consumption	
GTI	Green technological innovation	R&D expenditure (% of GDP), proxy for green technological innovation	
lnGDP	Economic growth	Constant 2015 US$	
Trade	Trade openness	Total trade (%of GDP)	

Model Specification

To investigate the interplay, between green technological innovation and renewable energy consumption on environmental quality, the following baseline panel model is specified:

$$CO2_{it} = \alpha_i + \beta_1 RNE_{it} + \beta_2 GTI_{it} + \beta_3 lnGDP_{it} + \beta_4 Trade_{it} + \varepsilon_{it}$$

Where,

$i = country\ (1-4)$

$t = time\ (2001-2024)$

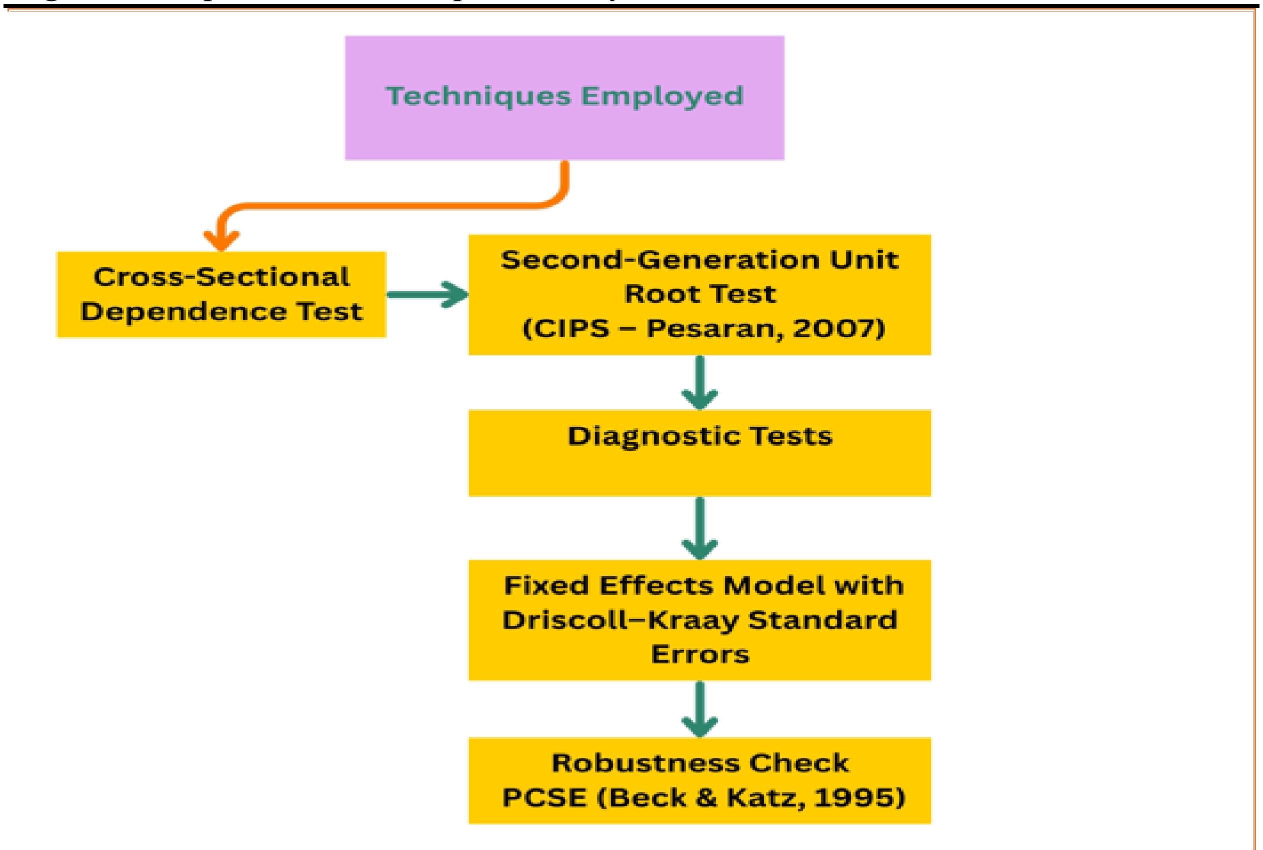
$\alpha_i = Country - specific\ fixed\ effects$

$\varepsilon_{it} = error\ term$

Econometric Strategies

Given the penalized structure of the data, we applied several diagnostic approaches. First, we tested for CSD by employing the Pesaran (2004) test, which indicated significant interdependence across countries and suggested the presence of common shocks.

Figure 2: Graphical Flow of Empirical analysis



The unit root of time series and pane time series to analysis the variable are unit root or not. If time series the nature of a variable to discuss the trend of the variable in single nature (Khan et al., 2023; Gul et al., 2023; Gul et al., 2023). Therefore, first-generation panel techniques are unsuitable, and we used second-generation CIPS (Pesaran, 2007) techniques to test for stationarity. The findings show most variables are integrated at I(1), while REC is stationary at this level, indicating a mixed order of integration. Further diagnostic checks indicate heteroscedasticity and slope heterogeneity (Pesaran and Yamagata, 2008), while the Wooldridge test shows the absence of significant first-order autocorrelation. Given cross-sectional dependence, heteroscedasticity, and heterogeneous slopes, traditional FE or RE estimators may provide biased inference (Khan et al., 2023; Zafar et al., 2025). To address this, we use a Fixed Effects estimator with Driscoll–Kraay (1998) standard errors, which are robust to CSD, heteroscedasticity, and autocorrelation. This estimator is used to estimate the baseline model. For robustness, we use the PCSE model and confirm the reliability of the results through consistency across estimators.

Results and Discussion

This unit shows and interprets the findings on the interplay among green technological innovations, REC, GDP, trade openness, and CO2 emissions. The study outcomes provide clear evidence on how REC and GTI enhance environmental sustainability. The descriptive statistics are shown in Table 2, which indicates that the average logged CO2 emissions are 1.395, with moderate variation across countries. The average REC is 25.61, indicating that renewable energy accounts for a considerable but unequal share of total energy consumption. GTI is 1.19 percent of GDP, indicating average innovation performance. The dispersion of logged GDP per capita is low, whereas the average trade openness is 41.74, highlighting the high level of global integration of the Big 4 economies. Table 3 reports the correlation matrix and VIF. The correlation matrix results indicate that Renewable energy (RNE) is highly negatively associated with Carbon emissions (-0.932), whereas GDP is positively associated with CO2 emissions (0.696). Furthermore, all VIFs are under 5, and the mean VIF is 2.72, indicating no severe Multicollinearity. This provides confidence in the CSD test, which shows cross-sectional dependence; therefore, estimation methods robust to this characteristic, such as Driscoll-Kraay standard errors, are used. Furthermore, the cross-sectional dependency results are shown in Table 4. The results indicated that all study variables exhibit significant CSD, as their p-value is less than 0.05. These sudden changes and shocks in one nation may influence other nations within this panel. Note: Figure 3 represents the graphical representations of correlation and Variance Inflation Factor.

Table 2: Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
CO2	96	1.395	0.879	-0.062	2.639
RNE	96	25.607	17.37	3.2	50
GTI	96	1.191	0.481	0.619	2.555
lnGDP	96	8.52	0.831	6.657	9.482
Trade	96	41.744	10.874	22.106	63.57

Table 3: Matrix of correlations and Variance Inflation Factor (VIF)

Variables	C02	RNE	R&D	lnGDP	Trade
CO2	1.000				
RNE	-0.932	1.000			
GTI	0.502	-0.365	1.000		
lnGDP	0.696	-0.400	0.569	1.000	
Trade	0.431	-0.649	-0.081	-0.203	1.000

	VIF	1/VIF
RNE	3.768	0.265
Trade	3.197	0.313
lnGDP	2.332	0.429
GTI	1.584	0.631
Mean VIF	**2.72**	

Figure 3: Correlation matrix and VIF

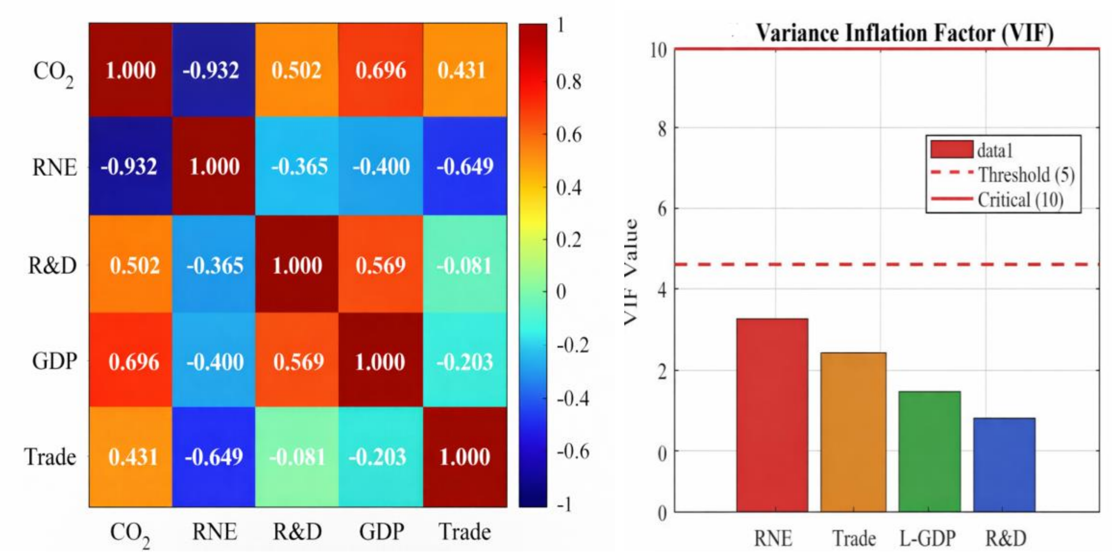


Table 4: Cross-sectional dependency

Variables	CD Statistics	p-value
CO2	8.35***	0.000
RNE	2.58**	0.010
GTI	-2.37**	0.018
lnGDP	10.99***	0.000
Trade	-2.40**	0.027

*, **, and *** refers 10%, 5% and 1% respectively.

Table 5 presents the outcomes of diagnostic tests, including the Modified Wald test, which indicates heteroscedasticity ($p < 0.01$), i.e., unequal panel variances. In contrast, the Wooldridge test fails to detect first-order autocorrelation ($p > 0.05$). Taken together, these results support the need to adopt powerful estimation methods to address heteroscedasticity. Furthermore, Table 6 presents the outcomes of the stationary, which indicate a mixed order; this further justifies the use of panel estimation techniques that accommodate such properties.

Table 5: Diagnostic test summary

Wald Test		Wooldridge test	
chi2 (4)	129.99	F (1, 3)	4.303
Prob > chi2	0.0000	Prob > F	0.1297

Table 6: Panel Unit Root (Pesaran, 2007) CIPS Results

Variable.	I(0)	I(1)	Order of Integration
CO2	-1.162	-2.407*	I(1)
RNE	-2.750**	-2.660**	I(0)
GTI	-1.847	-3.567***	I(1)
lnGDP	-2.236	-2.373*	I(1)
Trade	-0.797	-2.864**	I(1)

*, **, and *** refers 10%, 5% and 1% respectively. The CIPS critical values (N = 4, T ≈ 24) are −2.570, −2.330, and −2.210".

Finally, Table 7 presents the results of the Fixed-Effect model with Driscoll-Kraay standard errors, indicating that REC has a significant negative effect on CO2 emissions, suggesting that REC improves environmental quality in selected economies. Moreover, green technological innovations (GTI), GDP, and trade openness positively affect CO2 emissions. The estimated model has strong explanatory power (R2 = 0.9676). Furthermore, Table 8 displays the results of the PCSE model we used to assess robustness and confirm the stability and consistency of the Fixed-Effect model with the Driscoll-Kraay model. Across all estimators, renewable energy consistently has significant negative impacts on CO2 emissions, while GTI, GDP, and trade openness have significant positive impacts on CO2 emissions, further validating the empirical findings. The results highlight the importance of REC in significantly decreasing CO2 emissions in the Big Four emerging economies, showing its central role in supporting environmental sustainability. However, GTI is positively associated with carbon emissions, suggesting that current innovation efforts may continue to be linked to carbon-intensive industrial operations. Furthermore, trade openness and economic growth are strong contributors to increased carbon emissions in these economies.

Table 7: Fixed Effect Regression with Driscoll-Kraay standard Error Model

Variable	Coefficient	Std. Err.	T	P>z	[95% conf. interval]
RNE	-0.019***	0.003	-7.280	0.000	[-0.025,-0.014]
GTI	0.072***	0.022	3.29	0.001	[0.029, 0.115]
lnGDP	0.470***	0.035	13.620	0.000	[0.399,0.542]
Trade	0.003***	0.001	4.080	0.000	[0.002 0.005]
Constant	-2.342***	0.293	-8.000	0.000	[-2.947,-1.736]
Prob > F	0.0000	Group	4		
R^2	0.9676	observation	96		

*, **, and *** refers 10%, 5% and 1% respectively.

Table 8: Robustness PCSE Results

Variable	Coefficient	Std. Err.	T	P>z	[95% conf.interval]
RNE	-0.038***	0.001	-30.990	0.000	[-0.041, -0.036]
GTI	0.072***	0.020	3.60	0.000	[0.033, 0.111]
lnGDP	0.389***	0.026	15.010	0.000	[0.338, 0.440]
Trade	0.001**	0.001	3.810	0.021	[0.002, 0.028]
Constant	-0.978***	0.256	-3.820	0.000	[-1.480, -0.477]
Prob > F	0.0000	Group	4		
R^2	0.9668	observation	96		

*, **, and *** refers 10%, 5% and 1% respectively.

Conclusion and Recommendations

This paper examines how green technological innovation and renewable energy consumption (REC) affect CO2 emissions in four emerging economies, namely Brazil, Russia, India, and China, over the period from 2001 to 2024. These economies play a central role in global energy utilisation and environmental sustainability. Therefore, the relationships among innovation, energy transitions, and environmental outcomes are important. We employed the fixed-effects model with Driscoll-Kraay standard errors, which effectively addresses CSD, heteroscedasticity, and serial correlation problems commonly present in panel data. Renewable energy sources are considered a significant factor in improving environmental quality. However, CO2 is positively associated with GTI, trade openness, and economic growth. The results show that even though the REC increases economic growth and technological advancement in such economies. The study results suggested that greater expansion of renewable energy utilisation, along with a shift in green technological innovation, would lead to cleaner, more energy-efficient technologies. These would have helped align economic growth strategies with long-term environmental sustainability and simplify the shift to low-carbon development pathways in emerging economies.

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