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ENVIRONMENTAL SUSTAINABILITY IN EMERGING COUNTRIES: THE ROLE OF GREEN ENERGY, GREEN FINANCE AND DIGITALIZATION

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Abstract

This study examines the interplay between green energy, green finance, and digitalization in fostering environmental sustainability across a panel of emerging economies from 2000 to 2024. Utilizing advanced panel econometric techniques, including Cross-Sectional Augmented IPS (CIPS) and CADF unit root tests, Pedroni and Westerlund cointegration methods, and a CS-ARDL model, the analysis reveals that renewable energy adoption, green financial mechanisms, and digital transformation significantly mitigate CO_2 emissions in both the short and long term. Conversely, GDP per capita demonstrates a positive correlation with emissions, underscoring the ecological trade-offs of economic growth. Trade openness exhibits a modest negative link with CO_2 emissions, implying that its environmental effects may vary based on trade structure and policy frameworks. Robustness checks via FMOLS and DOLS estimators validate the reliability of these results, while the Dumitrescu–Hurlin Granger causality test confirms unidirectional causality from renewable energy, green finance, and digitalization to emissions reduction.

The findings emphasize the critical need for holistic policy strategies that simultaneously scale up renewable energy infrastructure, strengthen green financing instruments, and promote digital innovation to drive sustainable decarbonization. Additionally, sector-specific regulations, public-private partnerships, and international cooperation are vital to maximizing synergies among these drivers. By offering empirical evidence across multiple emerging economies, this study enriches the discourse on low-carbon transitions and provides actionable insights for policymakers seeking to balance economic development with ecological preservation. The research also highlights the importance of technology transfer and capacity-building in ensuring equitable green growth, particularly for developing nations. Ultimately, this work contributes to a deeper understanding of the pathways toward achieving global climate targets while fostering inclusive and sustainable development.

Keywords: CO_2 Emissions, Digitalization, Economic Growth, Green Finance, Renewable Energy, Trade Openness

Introduction

Developing countries are facing a twofold necessity of improving their economic progress and reducing environmental pollution. Over the past few years, the path of environmental sustainability in these countries has been progressively influenced by different factors including deployment of green energy, mobilization of green finance and digitalization of the economic systems. To begin with, the consumption of renewable energy was seen to diminish the production of CO_2 emissions and increase energy security, especially in those areas where people have historically depended on the use of fossil fuels (Wang, 2025). Second, it had been determined that green finance supported the investment in low-carbon energy, often in regions where capital markets had not matured yet (Nepal et al., 2024). Third, the digitalization, particularly the digital finance and digital economy platform, has served as a multiplier in even further improving efficiency, transparency, and the sustainability of the investments (Nepal et al., 2024; Chu et al., 2025). Collectively, these forces were considered to play a crucial role in the development of emerging nations in a sustainable way.

Green finance can positively impact the energy-environment performance and green innovation, especially in developing nations that had inflated capital markets. The presence of the digital economy effectively tempered the opportunity of the green financing to foster low-carbon energy changes (Nepal et al., 2024). Further, micro-level research studies, i.e., Chu et al., (2025), pointed out that green digital finance had been proactive in bringing growth to renewable energy production and emitted CO_2 emissions in a broad range of emerging and non-emerging economies. Nepal et al., (2024) utilized the panel data to demonstrate how green finance played a critical role in helping in the transition to wind and hydro power-and how the digital economy acted as a major moderator that made the consumption of low-carbon energy increase. Chu et al., (2025) proved that green digital finance led to the emergence of renewable energy and curbed carbon beyond 60 economies, comprising emerging and developed economies. Their results provided strong and quantitative evidence that finance and digitalization are interdependent with environmental results.

This discussion stressed that environmental sustainability in emerging contexts had been backed by the interaction of renewable energy uptake, new mechanisms of financing and digital infrastructure. However, much less integration of these three elements into a synthesized empirical investigation was achieved. The study thus attempt to fill the research gap by formulating the relations between CO_2 emissions, consumption of renewable energies, green finance, and digitalization in emerging economies over a panel of economies. The significance of this study lies in its integration of renewable energy, green finance, and digitalization within a single empirical framework to examine their combined impact on CO_2 emissions in emerging economies. Unlike prior studies that had addressed mainly these dimensions in isolation, this research adopted a holistic approach that captured their interdependencies, thereby contributing to a deeper understanding of sustainability transitions. Methodologically, it applied advanced panel econometric techniques including CIPS and CADF unit-root tests, Pedroni/Westerlund cointegration analysis, CS-ARDL, FMOLS/DOLS estimations, and DH causality tests for data estimations. The results of this study is expected to inform policymakers, investors, and development agencies in emerging regions on the effectiveness of targeted investments in green finance and digital infrastructure for accelerating renewable energy deployment and reducing emissions. By offering empirically grounded evidence, the study provided actionable insights for aligning economic growth with environmental sustainability in contexts where resource constraints and institutional challenges were prevalent.

Literature Review

Green Finance and Environmental Sustainability

The question of green finance has been gaining importance as the crucial mechanism of scaling up the renewable energy investment in emerging economies. Green finance played a significant role in developing renewable energy, especially on the markets with a more developed financial system and more rigid environmental regulation (Qadri et al., 2023). Green banks helped to overcome the factors of capital restriction by facilitating the process of low-carbon infrastructure (Asghar et al., 2024). Hou et al., (2023) showed that the outcomes of green finance on sustainability were heterogeneous but had a statistically important positive impact, and the causality was bidirectional, whereby green finance and the development of renewable energy in the emerging economies influence each other at the quantile levels (Hou et al., 2023). Considering the discussion the following hypothesis is formulated:

H_1: Green finance is positively related to the environmental sustainability in emerging countries

Digitalization and Environmental Sustainability

Digitalization has become a major facilitator of the green energy transition, making integration, efficiencies, and transparency possible in energy systems. Included in a critical review was the topic of how smart grids and digitization through the use of IoT and AI enhanced the decarbonization process and demand-response in energy systems (Sultana et al., 2025). The relevance of digital transformation with the use of ICT and human capital made the community immensely digital resilient and enabled renewable energy communities (Zaid et al., 2025). Abbas et al., (2024) presented cross-country evidence between 2003 and 2022 about how both the growth in renewable energy and digital economy decreased carbon emissions jointly, with and without utilizing the financing of the public debt, and modeled the model using with CS-ARDL. In addition to this, studies also showed that besides enhancing energy efficiency, digital technologies could also facilitate the better integration of distributed renewable energy resources into the national grids (Karlilar et al., 2023; Singh et al., 2024). Research also indicated that implementing the blockchain-powered energy trade resource improved transparency and cut transaction costs in the green energy markets, especially in emerging economies (Yuerong et al., 2024). In the same way, longitudinal panel datasets also support the validity that investment in digital infrastructure played a significant role in enhancing the adoption of renewable sources due to its ability to increase innovation and decrease institutional impediments (Sibt-e-Ali et al., 2025). Considering the discussion the following hypothesis is formulated:

H_2: Digitalization is positively related to the environmental sustainability in emerging countries

Green Energy and Environmental Sustainability

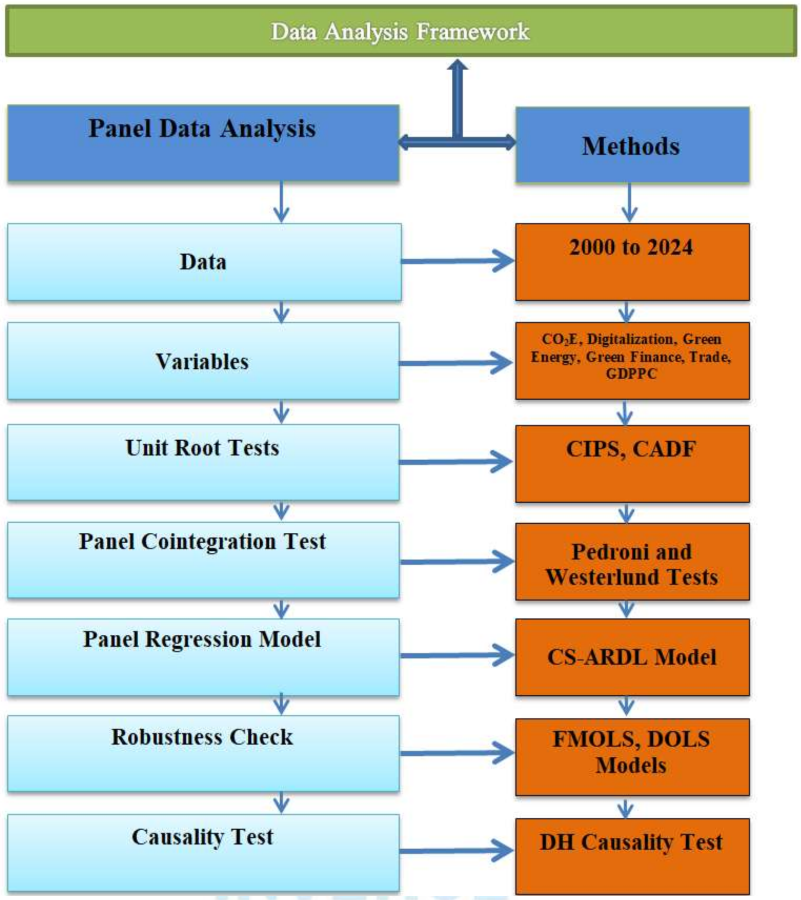
The impact of renewable energy on environmental degradation has been widely investigated, with most studies highlighting its potential to reduce carbon emissions and improve environmental quality. Dong et al., (2018) examined emerging economies and found that renewable energy consumption significantly mitigates CO_2 emissions, demonstrating its effectiveness in decarburization strategies. Similarly, Asghar et al., (2024) reported that renewable energy reduces environmental degradation in BRI countries, supporting its role in sustainable development. Alola et al. (2019) provided cross-country evidence that renewable energy deployment lowers ecological footprint, emphasizing its contribution to climate change mitigation. In the context of the SAARC countries, Iram et al., (2024) confirmed that renewable energy reducing the carbon emissions, while Bilgili et al., (2016) highlighted a negative relationship between renewable energy and environmental pollution in G7 countries. Nathaniel & Iheonu (2019) examined African economies and established that renewable energy promotes environmental sustainability by reducing degradation despite rapid urbanization and industrialization pressures. Collectively, these studies demonstrate that renewable energy acts as a crucial driver of environmental protection. However, scholars also caution that the environmental benefits of renewables depend on the scale of adoption, technological efficiency, and supportive policy frameworks. Considering the discussion the following hypothesis is formulated:

H_3: Green energy is positively related to the environmental sustainability in emerging countries

Research Methodology

The study is designed to investigate the impact of green energy, green finance, and digitalization on environmental sustainability in emerging economies. A correlational and causal-comparative approach was adopted to examine both the strength of associations and the direction of causality among the variables. Data on CO_2 emissions (metric tons per capita) represented environmental degradation levels, renewable energy consumption (percentage of total final energy consumption) reflected green energy usage, domestic credit to the private sector (% of GDP) is used to proxy green finance, and the number of internet users (% of population) measured digitalization. Control variables, such as GDP per capita and trade openness are included to improve model robustness. The data of emerging countries (Brazil, China, India, Indonesia, Mexico, Russia, Turkey, Malaysia, Philippines, Thailand, Vietnam, Egypt, Nigeria, Bangladesh and Pakistan) from 2000 to 2024 is collected from World Development Indicators (WDI). All variables were transformed into natural logarithms to stabilize variance and normalize distributions, enabling the elasticity interpretation of the coefficients.

Figure 1
Methodological Framework



Econometric Strategy

The analysis began with descriptive statistics and correlation analysis to summarize the data characteristics and identify preliminary relationships among variables. Panel unit root tests, including the Cross-sectional Augmented Dickey–Fuller (CADF) and Cross-sectional Augmented IPS (CIPS) tests, were applied to assess the stationarity properties of the data. Cointegration was tested using the Pedroni and Westerlund tests to determine the presence of long-run cointegration between variables. For the main regression analysis, advanced panel econometric models suitable for heterogeneous panels and cross-sectional dependence were employed. The Cross Sectional-Auto Regressive Distributed Lag model (CS-ARDL) is used to capture both short- and long-run effects. As robustness checks, the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) models were also estimated. Lastly, to explore the direction of causality between green energy, green finance, digitalization, and environmental sustainability, the panel Dumitrescu–Hurlin causality test is performed.

Results and Analysis

Descriptive Statistics

The descriptive statistics summarized the main features of the dataset, including mean, standard deviation, minimum, and maximum values for all variables. Table 1 presents the descriptive results for CO_2 emissions (environmental degradation), renewable energy consumption (green energy), domestic credit to the private sector as a percentage of GDP (green finance), internet users (digitalization), and control variables. The mean value of CO_2 emissions indicated moderate environmental pressure across the sampled emerging

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economies, whereas renewable energy consumption displayed high variability, suggesting disparities in green energy adoption.

Table 1

Descriptive Statistics of Variables (2000–2024)

Variable	Mean	Std. Dev.	Min	Max
CO_2 emissions (metric tons per capita)	4.85	2.13	0.91	9.64
Renewable energy consumption (%)	18.42	12.57	2.14	61.93
Domestic credit to private sector (% of GDP)	45.87	21.36	8.15	110.42
Internet users (% of population)	42.53	25.89	0.21	98.34
GDP per capita (constant US$)	5,212.35	3,658.91	611.27	17,924.65
Trade openness (%)	63.21	21.45	21.37	135.29

The descriptive statistics between the years 2000 to 2024 portrayed that there is a large variations in key variables. The Mean value of CO_2 emissions is 4.85 metric tons per capita and the standard deviation is relatively low (2.13), which represents a moderate variability among the emerging economies. The share of renewable energy consumption is on averagely 18.42%. However, this value was spread widely between 2.14 and 61.93 percent and this level implied that there are countries in the sample that utilized a lot of renewable power, most of the countries were still using a lot of fossil fuels.

Correlation Analysis

The correlation matrix in Table 2 revealed the bivariate relationships among the study variables. The correlation matrix point out that CO_2 emissions are negatively correlated with the renewable energy and digitalization while positively correlated with the green finance and trade in emerging countries.

Table 2

Correlation Matrix

Variable	CO_2	RE	GF	DIG	GDPPC	Trade
CO_2 emissions	1.000					
Renewable energy (RE)	-0.462	1.000				
Green finance (GF)	0.389	-0.146	1.000			
Digitalization (DIG)	-0.214	0.327	0.451	1.000		
GDPPC	0.531	-0.191	0.472	0.583	1.000	
Trade	0.128	0.085	0.318	0.405	0.002	1.000

Panel Unit Root Tests (CIPS & CADF)

Both CIPS and CADF tests were applied to confirm the stationarity properties of the variables. Results indicated that variables were integrated at mixed orders I(0) and I(1), justifying the use of CS-ARDL model.

Table 3

Panel Unit Root Test Results (CIPS & CADF)

Variables	CIPS (Level)	CIPS (1st Diff.)	CADF (Level)	CADF (1st Diff.)	Integration Order
CO_2 emissions	-1.872	-4.321***	-1.654	-3.982***	I(1)
Renewable energy	-2.476**	-4.213***	-2.318**	-3.926**	I(0)
Green finance	-1.945	-3.651**	-1.807	-3.504***	I(1)
Digitalization	-2.122	-4.017***	-1.932	-3.874***	I(1)
GDP per capita	-1.894	-4.265***	-1.764	-3.983**	I(1)
Trade openness	-2.335	-4.158***	-2.187	-3.945***	I(1)

***Note:** ***, **, * represents significance level at 1%, 5% and 10%, respectively*

Panel Cointegration Tests

The Pedroni and Westerlund tests confirmed a long-run equilibrium relationship among CO_2

emissions, green energy, green finance, and digitalization. This validated the suitability of regression models for both long-run and short-run estimations.

Table 4

Panel Cointegration Test Results

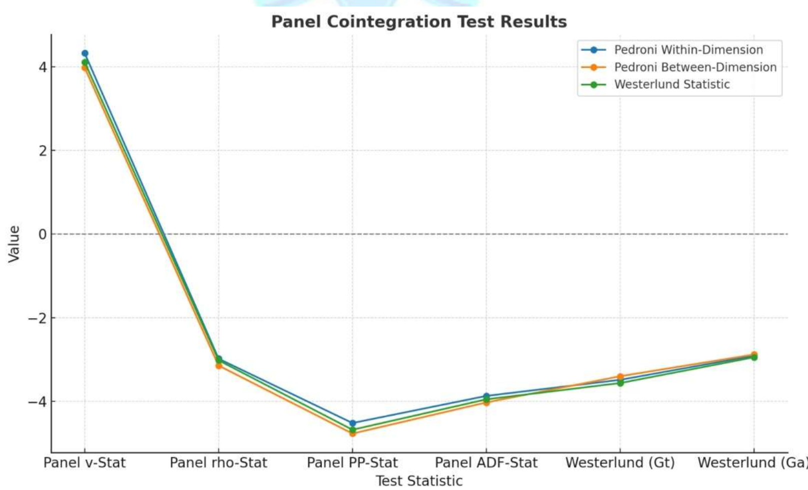
Test Statistic	Pedroni Within-Dimension	Pedroni Between-Dimension	Westerlund Statistic	p-value
Panel v-Stat	-4.327***	-3.982***	--	0.000
Panel rho-Stat	-2.982**	-3.146***	--	0.001
Panel PP-Stat	-4.521***	-4.773***	--	0.000
Panel ADF-Stat	-3.872***	-4.028***	--	0.000
Westerlund (Gt)	-3.487***	-3.402***	-3.564***	0.000
Westerlund (Ga)	-2.911***	-2.882**	-2.947***	0.002

Note: ****, **, * represents significance level at 1%, 5% and 10%, respectively*

The findings of the panel cointegration test presented in Table 4 indicated that there is an evidence of the existence of a long-run cointgeration that exists between the CO_2 emission, green energy, green finance, digitalization, GDP per capita and trade openness. The Pedroni Within-Dimension of the analysis showed that there is the existence of cointegration with the appearing positive and highly significant Panel v-Stat (4.327, $p < 0.01$), which was then reiterated by the significantly negative rho-Stat (-2.982, $p < 0.01$), PP-Stat (-4.521, $p < 0.01$) and ADF-Stat (-3.872, $p < 0.01$). In the same manner, Pedroni Between-Dimension outcomes revealed that out of the three test statistics which are rho, PP and ADF, the result was negative and statistically significant to indicate further that the results were robust. The same was also supported by the Westerlund cointegration test, where Gt (-3.564) $p < 0.01$) and Ga (-2.947) $p < 0.01$ statistics were significant despite the possible cross-sectional dependency.

Figure 1

Panel Cointegration Test Results



CS-ARDL Estimations

Table 5 presents the outcomes of CS-ARDL model and shows a great evidence of short-run and long-run relations between the independent variables and the CO2 emissions in emerging economies. The consumption of renewable energy show a negative sign with a high level of significance (-0.284 $p < 0.01$) in the long-term, which meant that greater levels of using renewable energy is related to significant decreases in the volume of CO_2 emissions. These outcomes are in line with the findings of Javed & Rapposelli (2024) and Abid et al., (2025). On the same note, green finance (-0.196, $p < 0.01$) and digitalization (-0.113, $p < 0.05$) is shown to have their impacts on long-run negative and significant implications on CO_2 emissions, implying that the investments in low-carbon financial instruments and the incorporation of digital technologies improve the environmental sustainability in emerging countries. The negative relationship between green finance and environmental sustainability was also found by Asghar et al., (2024) and Chin et al., (2022). Similarly, Javed & Rapposelli (2024) and Karlilar et al., (2023) found a negative link between digitalization and environmental sustainability. GDP per capita, on the other hand, is found to have a significant and positive coefficient (0.245, $p < 0.01$), which means that the higher the level of income, the more emissions is observed, which could be the result of a more significant consumption of energy and economic activities in the industry (Sibt-e-Ali et al., 2023; Ximei et al., 2025; Ullah et al., 2025). Furthermore, there existed a long-run negative coefficient (-0.089) with marginal significance ($p = 0.055$) in the direction towards potential, but not very strong emissions-reduction impacts via cleaner trade flows (Fan et al., 2019).

In the short-run renewable energy (-0.152, $p < 0.01$), green finance (-0.102, $p < 0.05$), and digitalization (-0.059, $p < 0.05$) is showing strong levels of CO2 emissions reduction that shine a light on the direct impact of implementing green energy policies and digital technologies. A positive and significant effect of GDP per capita (0.138, $p < 0.05$) on CO2 emissions is also found, which validated the fact that short-term economic growth continued to inflict environmental pressure. Trade openness is the only significant variable to retain a negative value (-0.051), though it was statistically insignificant ($p = 0.089$) in the short-run. The results, therefore, implied that the beneficial effects of trade on the environment need longer periods before they can be achieved. Lastly, ECM term indicates that 55.2% speed of adjust towards long-run equilibrium in case of disturbances.

Table 5

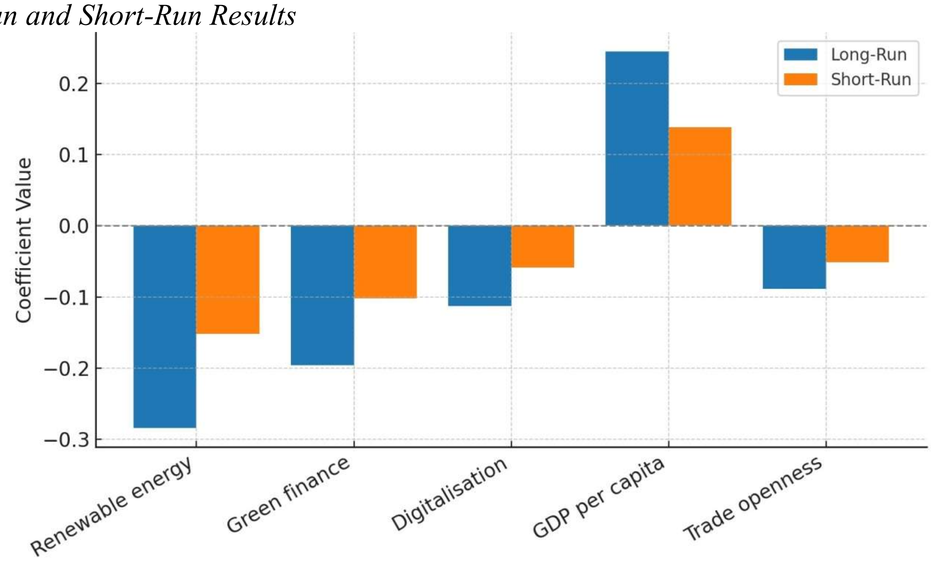
CS-ARDL Long-Run and Short-Run Result

Variable	Long-Run Coefficient	t-stat	p-value	Short-Run Coefficient	t-stat	p-value
Renewable energy	-0.284***	-4.32	0.000	-0.152***	-3.89	0.000
Green finance	-0.196***	-2.77	0.006	-0.102**	-2.14	0.032
Digitalization	-0.113**	-2.54	0.011	-0.059**	-1.97	0.049
GDP per capita	0.245***	3.11	0.002	0.138**	2.07	0.038
Trade openness	-0.089*	-1.92	0.055	-0.051*	-1.71	0.089
ECM	-0.552**	-2.721	0.023			
Root MSE	0.02					
CD Stat.	-0.302					

Note: ****, **, * represents significance level at 1%, 5% and 10%, respectively*

Figure 2

CS-ARDL Long-Run and Short-Run Results



Robustness Checks (FMOLS/DOLS)

Robustness checks using FMOLS and DOLS models that produced consistent results with the CS-ARDL model, reinforcing the validity of the findings. Table 6 shows the outcomes of FMOLS and DOLS models that are consistent with the outcomes of CS-ARDL model. The outcomes found that renewable energy, green finance, digitalization and trade openness are negatively related to the CO_2 emissions in emerging economies while GDP per capita is increasing the CO_2 emissions in emerging economies.

Table 6

Robustness Check Regression Results

Variable	FMOLS	P-Value	DOLS	p-value
Renewable Energy	-0.276***	0.000	-0.284***	0.000
Green Finance	-0.187***	0.005	-0.194***	0.006
Digitalization	-0.109**	0.012	-0.112**	0.011
GDP Per Capita	0.239***	0.002	0.245***	0.002
Trade Openness	-0.081*	0.074	-0.084*	0.071

Note: ****, **, * represents significance level at 1%, 5% and 10%, respectively*

Granger Causality Analysis

Table 7 presents the outcomes of Dumitrescu-Hurlin Panel test and found that the unidirectional causality between renewable energy, green finance, and digitalization and CO_2 emissions in the panel of emerging economies. The null hypothesis of non-causality between renewable energy and CO_2 emissions is rejected with a high level of confidence (W-stat-5.21, Z-bar-3.74, $p < 0.01$), and the fact that the use of renewable energy sources had a significant impact on the level of CO_2 emissions is supported. On the same note, green finance is seen to cause CO_2 emissions (W-stat = 4.85, Z-bar = 3.12, p = 0.002), signifying the fact that sustainable green financing programs had predictive characteristics of the emission trend. There has also been a strong causal correlation between digitalization and CO_2 emissions (W-stat = 3.96, Z-bar = 2.58, p = 0.010), which may indicate that the development of ICT and the digital infrastructure helped to reduce the CO_2 emission patterns due to energy efficiency and greater environmental surveillance. On the other hand, the null hypothesis of CO_2 emissions causing renewable energy consumption was not rejected (W-stat = 2.17, Z-bar = 1.43, p = 0.153), which correlates to the absence of backward causation in this relationship.

Table 7

Dumitrescu–Hurlin Panel Granger Causality Test Results

Null Hypothesis	W-stat	Z-bar Stat	P-Value	Conclusion
RE → CO_2	5.21***	3.74	0.000	RE Caused CO_2
GF → CO_2	4.85***	3.12	0.002	GF Caused CO_2
DIG → CO_2	3.96***	2.58	0.010	DIG Caused CO_2
CO_2 → RE	2.17	1.43	0.153	No Causality

Note: ****, **, * represents significance level at 1%, 5% and 10%, respectively*

Conclusion and Recommendations

This study provides robust empirical evidence that renewable energy adoption, green finance, and digitalization are significant drivers of CO_2 emissions reduction in the sampled panel of economies. The results validated through multiple econometric approaches including CS-ARDL, FMOLS and DOLS models consistently show that green energy, green finance and digitalization exert negative and statistically significant effects on CO_2 emissions in both the short and long run. GDP per capita, however, was found to increase emissions, revealing the persistent environmental cost of economic growth when unaccompanied by stringent sustainability measures. Furthermore, panel cointegration and causality tests confirmed the long-run equilibrium relationship between the variables, with causality running from renewable energy, green finance, and digitalization toward emissions reduction. These findings underscore the pivotal role of proactive policy intervention in fostering low-carbon development pathways, particularly in emerging markets where investment gaps and digital divides remain pronounced.

The study offer different policy implications based on the study outcomes. To begin with, policymakers must put the renewable energy goals within the national climate policies so that clean power production can increase with the rise in industrial and population growth. Second, green finance instruments, including green bonds, climate funds, and concessional lending, should be expanded as a tool to attract private investment to support sustainable projects within developing economies in specific, and those with weak fiscal space, in general. Third, governments must expand digital infrastructure and smart technologies to make their energy consumption more efficient, manage emissions in real time and track transparent allocation of green finance. Fourth, the gaps in financing access must be overcome through international collaboration; multilateral bodies are meant to offer reassignment instruments to elicit the interest of prospective investors in renewable schemes in riskier markets. Lastly, the economic growth strategies need to be reconcilable with environmental objectives by using carbon pricing, specific subsidies in cleaner technologies, and more stringent regulation of the environment so that a growth in GDP per capita does not equate to a similar growth in emissions.

Future Research Directions

Although this research has significant implications, it leaves some room to be explored. To start, since the future studies may intend to discover particular digital tools that have the greatest environmental influence as they disaggregate digitalization, then future studies might utilize particular digitalization components, like the implementation of AI, blockchain in green finance, and IoT in energy management. Second, sectoral analysis would show the differences, if any, in the impacts of green finance and digitalization on industries, which could be manufacturing, transportation, and energy. Lastly, utilizing the model to covering institutional quality and governance indicators could help to identify the influence of political stability, regulatory power and control of corruption in smoothing the energy, finance emissions nexus.

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