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Renewable Energy Transition and Ecological Sustainability in N-11 Economies: The Critical Roles of Innovation and Financial Development

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Abstract

Ecological sustainability has become a major concern for emerging economies; however, evidence regarding the combined effects of Financial Development (FD), Technological Innovation (TEI), Renewable Energy Transition (RET), and particularly the interaction between TEI and RET remains limited for N-11 economies. To fill this gap, this study examines the impacts of FD, TEI, RET, green growth, and their interaction effect on ecological sustainability in N-11 economies during 2005-2024 using Mean Group Common Correlated Effects (MG-CCE) and Mean Group Fully Modified Ordinary Least Squares (MG-FMOLS) estimators. The results indicate that FD, TEI, RET, and green growth significantly enhance ecological sustainability. More importantly, the interaction between TEI and RET is positive and significant, suggesting that innovation strengthens the environmental benefits of renewable energy adoption. Therefore, policymakers should integrate renewable energy policies with innovation-driven technological strategies to accelerate ecological sustainability and strengthen long-term environmental resilience in N-11 economies.

Keywords: Ecological sustainability, Technological innovation, Renewable energy transition, Financial development, Green growth.

1 | Introduction

Environmental sustainability has become one of the most critical global challenges confronting emerging economies, particularly those experiencing rapid industrialization, urbanization, and energy-intensive economic expansion [1–3]. The N-11 economies, including Bangladesh, Egypt, Indonesia, Iran, Mexico,

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Nigeria, Pakistan, the Philippines, South Korea, Turkey, and Vietnam, have attracted considerable attention due to their substantial economic growth potential and increasing contribution to global production and energy consumption [4]. However, the growth trajectory of these countries has been accompanied by rising ecological degradation, excessive resource exploitation, and increasing pressure on environmental systems [5]. Rapid industrial growth and urban expansion in these economies have intensified dependence on fossil-fuel-based energy sources, thereby increasing ecological imbalance and environmental deterioration. Moreover, the accelerating pace of manufacturing activities in the N-11 region has contributed to higher ecological footprints and environmental stress, threatening the long-term sustainability of economic development [4]. Consequently, achieving ecological sustainability while maintaining economic growth has become a strategic policy objective for these emerging economies. In this regard, evaluating the determinants of environmental quality and ecological sustainability is essential for developing balanced economic and environmental policies capable of supporting sustainable development goals in the N-11 countries.

Technological Innovation (TEI) plays a pivotal role in addressing environmental degradation by improving production efficiency, reducing energy waste, and supporting the diffusion of environmentally friendly technologies [6]. Innovation-driven development contributes to cleaner production systems and facilitates the transition toward low-carbon economic structures [1]. According to Schumpeterian innovation theory, technological progress stimulates productivity growth while simultaneously enabling the adoption of advanced environmental technologies that mitigate ecological damage [7]. In the context of N-11 economies, TEI has become increasingly important because these countries are undergoing structural economic transformation and industrial modernization [8]. Green innovation, eco-efficient industrial processes, and sustainable technological development can substantially reduce emissions and ecological pressure through enhanced resource efficiency and cleaner energy utilization [9]. Furthermore, TEI supports the development of smart production systems and environmentally sustainable infrastructure capable of reducing ecological footprints. Nevertheless, empirical findings regarding the environmental consequences of TEI remain inconclusive, especially in emerging economies characterized by heterogeneous institutional structures and varying levels of technological capability [10], [11]. Therefore, examining the environmental implications of TEI in the N-11 countries remains highly important for understanding sustainable economic transformation processes.

Renewable Energy Transition (RET) has emerged as a fundamental pillar of ecological sustainability because of its potential to reduce carbon emissions, improve energy security, and support sustainable economic growth [12]. The increasing energy demand associated with industrialization and urbanization in the N-11 economies has intensified environmental degradation due to excessive dependence on conventional fossil fuels [13]. In response to these environmental concerns, several N-11 countries have increasingly invested in renewable energy infrastructure and clean energy technologies to facilitate the transition toward sustainable energy systems. Renewable energy consumption contributes significantly to mitigating ecological deterioration by reducing greenhouse gas emissions and lowering ecological footprints [14]. Previous empirical studies have confirmed that renewable energy utilization improves environmental quality in both developed and developing economies [15], [16]. Additionally, renewable energy enhances sustainable economic development by promoting cleaner industrial production and decreasing environmental externalities associated with fossil-fuel consumption [17]. Nevertheless, the effectiveness of renewable energy policies depends substantially on technological capabilities, institutional frameworks, and financial support mechanisms. Accordingly, investigating the role of renewable energy in improving ecological sustainability within the N-11 countries is crucial for designing effective environmental and energy policies.

Financial Development (FD) is another critical determinant of environmental sustainability because financial systems influence investment allocation, industrial expansion, TEI, and energy consumption patterns [18–20]. A developed financial sector can facilitate ecological sustainability by financing renewable energy projects, supporting environmentally friendly technologies, and promoting green industrial transformation [21]. Financial institutions may contribute positively to environmental quality through green financing mechanisms, environmentally responsible investment policies, and sustainable credit allocation [22]. At the same time, FD may also stimulate environmentally harmful economic activities by increasing industrial production, consumer spending, and energy-intensive investments, thereby exacerbating ecological degradation [23]. In emerging economies such as the N-11 countries, expanding financial systems often support industrialization and infrastructure development, which can simultaneously generate economic growth and environmental pressure. Existing empirical studies provide mixed findings regarding the environmental consequences of FD, with some studies identifying environmentally beneficial effects while others report adverse ecological outcomes [24], [25]. Therefore, examining the role of FD in ecological sustainability remains highly important for understanding how financial systems can support sustainable development in rapidly growing economies.

Beyond the direct environmental implications of TEI, it may also indirectly influence ecological sustainability by strengthening the environmental effectiveness of renewable energy systems. Technological advancement enhances renewable energy efficiency through improvements in energy storage systems, transmission infrastructure, smart grids, and cleaner production technologies [26]. In this regard, TEI may function as a moderating mechanism that amplifies the positive impact of renewable energy on ecological sustainability. Innovation-driven renewable energy systems facilitate sustainable industrial production, reduce ecological pressure, and improve environmental resilience through enhanced energy efficiency and cleaner technological integration [27]. In N-11 economies, where RET processes are still evolving, TEI can significantly improve the performance and adoption of renewable energy systems. Recent evidence suggests that innovation-based sustainable energy technologies contribute substantially to reducing ecological footprints and supporting carbon neutrality objectives in emerging economies [4]. Therefore, analyzing both the direct and moderating effects of TEI on environmental quality through renewable energy channels provides a more comprehensive understanding of ecological sustainability dynamics within the N-11 region.

The N-11 economies were selected for this study because they represent a strategically important group of emerging countries characterized by rapid industrialization, expanding populations, increasing urbanization, and growing energy demand. According to global economic projections, the N-11 economies possess substantial potential to become major contributors to future global economic growth due to their favorable demographic structures, expanding industrial sectors, and increasing integration into international trade networks [4]. Despite this economic potential, these economies continue to experience severe environmental challenges associated with fossil-fuel dependence, rising ecological degradation, increasing ecological footprints, and unsustainable production systems [5]. The rapid expansion of manufacturing activities and energy consumption in these countries has intensified environmental pressure and increased ecological vulnerability over recent decades [4]. Furthermore, the N-11 countries exhibit substantial heterogeneity in terms of technological capacity, renewable energy development, financial systems, and environmental policy frameworks, making them highly suitable for investigating the determinants of ecological sustainability. In addition, many N-11 economies have increasingly adopted renewable energy strategies and sustainable development policies to address environmental degradation and climate change challenges. Therefore, studying ecological sustainability in the N-11 countries provides valuable policy insights into how emerging economies can achieve sustainable environmental transformation while maintaining long-term economic growth.

Although the existing literature has extensively investigated the relationship between economic growth, energy consumption, and environmental degradation, several important research gaps remain unresolved. First, most previous studies have relied primarily on carbon dioxide emissions as a proxy for environmental degradation, while relatively few studies have employed broader indicators such as LCF, which provides a more comprehensive measure of ecological sustainability. Second, prior empirical studies have generally analyzed TEI, renewable energy, and FD separately rather than simultaneously examining their combined influence on ecological sustainability. Third, despite growing interest in green technological transformation, limited empirical attention has been devoted to investigating the moderating role of TEI in strengthening the environmental effectiveness of renewable energy systems, particularly within the context of N-11 economies. Fourth, the majority of previous studies have concentrated on developed economies or large emerging economies such as BRICS countries, while the N-11 economies have received comparatively limited scholarly attention despite their growing importance in the global economy and environmental sustainability discourse. Finally, empirical evidence regarding the environmental implications of FD and TEI remains mixed and inconclusive in emerging economies, highlighting the need for further investigation.

Drawing upon the above discussion, the primary objective of this study is to examine the impacts of TEIs, renewable energy consumption, and FD on ecological sustainability in the N-11 economies using the LCF as an indicator of environmental quality. The study seeks to investigate whether TEI contributes to ecological sustainability through cleaner production systems, energy efficiency improvements, and environmentally friendly technological diffusion. Additionally, the study aims to evaluate the role of renewable energy in mitigating environmental degradation and enhancing ecological sustainability in emerging economies. Furthermore, the study investigates whether FD supports ecological sustainability through environmentally responsible investment and green financing mechanisms. Another important objective of this study is to analyze the moderating role of TEI in the relationship between RET and ecological sustainability. Specifically, the study aims to determine whether technological advancement strengthens the environmental benefits of RET in the N-11 countries. By incorporating interaction effects into the analytical framework, the study seeks to provide a deeper understanding of how TEI and RET jointly contribute to improving ecological sustainability and supporting sustainable development objectives in emerging economies.

Building on the research objectives, this study seeks to answer several important research questions. First, do TEIs significantly improve ecological sustainability in the N-11 economies? Second, does RET contribute positively to LCF and environmental quality? Third, what is the effect of FD on ecological sustainability within the N-11 countries? Fourth, does TEI strengthen the environmental impact of RET through a moderating mechanism? Finally, how can policymakers in emerging economies design integrated environmental, technological, and financial policies to achieve ecological sustainability while maintaining economic growth?

The remainder of this study is organized as follows. The next section reviews the relevant empirical literature concerning ecological sustainability, TEI, RET, and FD. Subsequently, the methodology and econometric model specifications are presented. The following section reports and discusses the empirical findings. Finally, the study concludes with key findings, practical policy recommendations, study limitations, and suggestions for future research avenues related to ecological sustainability and sustainable energy transition in for the N-11 economies.

2 | Literature Review and Research Hypotheses

This section reviews the existing theoretical and empirical literature related to TEI, RET, FD, and ecological sustainability. Furthermore, it discusses the conceptual relationships among the study variables and develops the research hypotheses based on previous findings and theoretical arguments.

2.1 | Technological Innovation and Ecological Sustainability

The relationship between TEI and environmental sustainability has received growing attention in environmental economics literature. TEI is generally viewed as an essential driver of ecological sustainability because it promotes cleaner production systems, energy efficiency, and environmentally friendly industrial transformation. Qamruzzaman et al. [1] argued that research and development activities significantly reduce carbon emissions by facilitating energy-efficient technologies and cleaner production methods. Similarly, Demir et al. [8] demonstrated that innovation-driven industrial systems contribute positively to environmental quality through eco-friendly technological transformation. Mehmood et al. [9] emphasized that technological advancement improves environmental performance by reducing production inefficiencies and supporting low-carbon industrialization. Han and Cai [4] also found that TEI significantly mitigates ecological footprints in N-11 economies through sustainable energy technologies and environmentally efficient production systems. However, some empirical studies report mixed evidence, suggesting that TEI may simultaneously stimulate industrial expansion and energy consumption, thereby increasing ecological pressure in developing economies. In this regard, TEI contributes to environmental sustainability by improving energy efficiency, supporting cleaner production systems, and reducing ecological degradation. Previous studies indicate that innovation-driven industrial transformation facilitates sustainable economic growth and environmental improvement. Based on the above empirical evidence, the following hypothesis is proposed:

H1: TEI positively influences ecological sustainability in N-11 economies.

2.2 | Renewable Energy Transition and Environmental Quality

RET has emerged as a crucial component of sustainable development because it reduces dependence on fossil fuels and mitigates greenhouse gas emissions. Dong et al. [14] reported that renewable energy consumption significantly reduces environmental degradation by lowering carbon emissions and improving ecological sustainability. Similarly, Nathaniel and Khan [28] found that renewable energy plays a vital role in reducing ecological footprints in emerging economies. Sahoo and Sethi [16] concluded that renewable energy consumption positively influences environmental quality through cleaner energy utilization and sustainable industrial development. Furthermore, renewable energy contributes to energy security, economic diversification, and sustainable growth by reducing the environmental externalities associated with fossil-fuel consumption. Therefore, renewable energy reduces dependence on fossil fuels and lowers greenhouse gas emissions, thereby improving environmental quality and ecological sustainability. Given the preceding discussion and the existing empirical findings, the following hypothesis is formulated:

H2: RET positively affects ecological sustainability in N-11 economies.

2.3 | Financial Development and Ecological Sustainability

The relationship between FD and environmental sustainability remains controversial in the empirical literature. Tamazian et al. [21] argued that developed financial systems can improve environmental quality by supporting green investment and environmentally sustainable projects. Similarly, Zaidi et al. [22] emphasized that financial institutions can facilitate ecological sustainability through sustainable financing mechanisms and green credit allocation. Conversely, Murshed et al. [23] reported that FD may intensify environmental degradation by stimulating industrial production, consumer spending, and energy-intensive activities Nathaniel [24] also found mixed evidence regarding the environmental implications of FD in emerging economies. For this reason, financial systems may either support environmental sustainability through green investment or exacerbate ecological degradation through energy-intensive industrial expansion. Therefore, further empirical investigation is required to understand the environmental consequences of FD in the context of N-11 economies. Considering the aforementioned empirical insights, the following hypothesis is developed:

H3: FD significantly influences ecological sustainability in N-11 economies.

Beyond direct environmental implications of TEI, it may also indirectly influence ecological sustainability by strengthening the environmental effectiveness of RET. Technological advancement enhances renewable energy efficiency through improvements in energy storage systems, transmission infrastructure, smart grids, and cleaner production technologies [26]. In this regard, TEI may function as a moderating mechanism that amplifies the positive impact of renewable energy on ecological sustainability. Innovation-driven renewable energy systems facilitate sustainable industrial production, reduce ecological pressure, and improve environmental resilience through enhanced energy efficiency and cleaner technological integration [27]. In N-11 economies, where RET processes are still evolving, TEI can significantly improve the performance and adoption of renewable energy systems. Recent evidence suggests that innovation-based sustainable energy technologies contribute substantially to reducing ecological footprints and supporting carbon neutrality objectives in emerging economies [4]. Therefore, analyzing both the direct and moderating effects of TEI on environmental quality through renewable energy channels provides a more comprehensive understanding of ecological sustainability dynamics within the N-11 region. In this context, technological advancement strengthens the positive environmental impact of renewable energy by improving renewable energy efficiency, reducing operational costs, and facilitating sustainable energy transition.

H4: TEI moderates the ecological effectiveness of RET.

3 | Data and Methodology

3.1 | Sample and Description of Data

This study investigates the relationship between TEI, RET, FD, and ecological sustainability, proxied by LCF in N-11 economies, sample including Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, the Philippines, South Korea, Turkey, and Vietnam, over the period 2005-2024. The. *Table 1* represents the symbol, name, measurement units, and sources of the variables. The data on LCF is aggrandized from the GFN database. The data on RET (renewable energy, % of total energy), FD (percentage of GDP), TEI (patent resident and non-resident), and Green Economic Growth (GG) (% of GNI) is aggrandized by WDI database.

Table 1. Variables, definitions and data sources.

Description	Symbol	Measurement Unit	Source
LCF	LCF	biocapacity / ecological footprint	GFN
Financial development	FD	Domestic credit to private sector (percentage of GDP)	WDI
Technological innovation	TEI	Combination of both patent resident and non-resident	WDI
Renewable energy transition	RET	Renewable energy consumption (% of overall energy use)	WDI
Green economic growth	GG	Adjusted net savings, including particulate emission damage (% of GNI)	WDI

Note: GFN denotes global footprint network and WDI indicates world development indicators.

Additionally, *Fig. 1* illustrates the geographical distribution of the selected countries, with their economies classified according to LCF levels. Among them, Indonesia demonstrates the highest performance with a score of 0.65, while South Korea exhibits the lowest performance at 0.11.

Fig. 1. Geographical coverage of N-11 economies in 2024 based on the LCF.

3.2 | Methodology and Model Construction

Drawing on established empirical literature, the baseline specification of the model is expressed as:

$$\ln LCF_{it} = \beta_0 + \beta_1 \ln FD_{i,t} + \beta_2 \ln TEI_{i,t} + \beta_3 \ln RET_{i,t} + \beta_4 \ln GG_{i,t} + \beta_5 \ln(RET_{i,t} \times TEI_{i,t}) + \varepsilon_{i,t}, \quad (1)$$

where i (I = 1, 2, 3, …, 11) and t (t = 2005-2024) denote countries and time, respectively. LCF_{it} represents ecological sustainability, $\ln FD_{i,t}$ shows FD, $\ln TEI_{i,t}$ represents RET, $GG_{i,t}$ denotes GG, $(RET_{i,t} \times TEI_{i,t})$ denotes the moderating role of TEI in ecological effectiveness of RET.

To account for Cross-Sectional Dependence (CSD) and heteroskedasticity within the panel dataset, this study employs the Mean Group Common Correlated Effects (MG-CCE) estimator. Originally introduced by Pesaran [29] and subsequently extended by Kapetanios et al. [30], the CCEMG approach provides a reliable framework for addressing potential estimation biases arising from unobserved common factors and cross-sectional interdependencies. One of the key advantages of this estimator is its ability to accommodate structural breaks and non-stationary unobserved common components within heterogeneous panel settings [31]. The CCEMG methodology incorporates cross-sectional averages of both dependent and independent variables to capture the influence of latent common effects across panel units [29]. Furthermore, in the presence of heterogeneous slope coefficients across countries, the CCEMG estimator enables robust panel-wide inference by allowing parameter heterogeneity among cross-sectional units. The CCEMG specification can be expressed as follows:

$$y_{it} = \alpha_i + \beta_i x_{it} + c_i f_t + \bar{y}_{it} + \bar{x}_{it} + \varepsilon_{it}, \tag{2}$$

where y_{it} and x_{it} represent the observable dependent and independent variables, respectively; β_i denotes the country-specific slope coefficients; f_t refers to the unobserved common factors with heterogeneous factor loadings; while α_i and ε_{it} indicate the intercept and error term, respectively. According to Eq. (1), the study-specific CCEMG model is specified as follows:

$$\begin{aligned}\ln \mathrm{LCF}_{it} = \alpha_i + \beta_{1i} \ln \mathrm{FD}_{it} + \beta_{2i} \ln \mathrm{TEI}_{it} + \beta_{3i} \ln \mathrm{RET}_{it} + \beta_{4i} \ln \mathrm{GG}_{it} + \beta_{5i} \ln(\mathrm{RET}_{it} \times \mathrm{TEI}_{it}) \\ + \lambda_i \bar{Z}_t + \varepsilon_{it},\end{aligned} \tag{3}$$

where LCF denotes the LCF, FD represents FD, TEI indicates TEI, RET refers to RET, and GG is included as a control variable. The interaction term (RET×TEI) captures the moderating role of TEI in the relationship between RET and ecological sustainability. Moreover, $\bar{Z}_t$ represents the vector of cross-sectional averages of the dependent and explanatory variables, which is incorporated to control for unobserved common factors and CSD across countries. To ensure the robustness and reliability of the empirical findings, this study additionally employs the Mean Group Fully Modified Ordinary Least Squares (MG-FMOLS) estimator. This estimation technique is particularly appropriate in heterogeneous panel frameworks, as they effectively account for both CSD across countries and slope heterogeneity among panel units. *Fig. 2* shows the flow chart of the econometric modelling process that this paper follows.

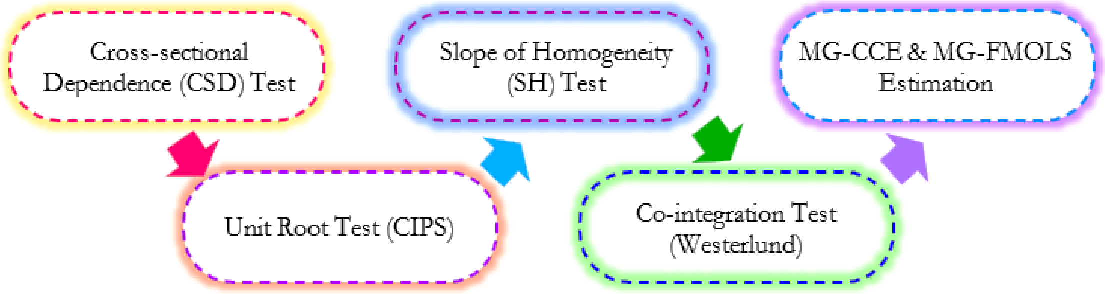


Fig. 2. Flow chart of econometric modelling process.

4 | Results Analysis and Discussion

The empirical analysis of panel data initially requires the assessment of CSD among the panel units. To this end, the present study employs the Breusch–Pagan LM test and the Pesaran scaled LM test to detect potential cross-sectional interdependencies. The findings of these tests, presented in *Table 2*, strongly reject the null hypothesis of cross-sectional independence. This result indicates the existence of significant interconnections among the sampled countries, implying that economic or environmental shocks occurring in one country may transmit and exert spillover effects on other countries within the panel dataset.

Table 2. Cross sectional test dependence result.

	lnLCF	lnFD	lnTEI	lnRET	lnGG
Breusch-Pagan LM	6048.03*	530.75*	508.12*	885.09*	880.09*
Pesaran scaled LM	40.330*	62.855*	56.576*	78.051*	79.220*

Note: * denotes the significance level at 1%.

Given the presence of CSD among the panel units, the application of second-generation panel unit root tests becomes necessary, as these approaches effectively account for cross-sectional interdependencies. Accordingly, this study proceeds to examine the stationarity properties of the variables under investigation. The results reported in *Table 3* reveal that the null hypothesis of a unit root cannot be rejected at the level form of the variables. However, after taking the first difference, all variables become stationary at the 1% significance level, confirming that the series are integrated of order one, I(1).

Table 3. Panel unit root test results.

	CIPT Test (Level)	CIPS Test (First Difference)
lnLCF	-2.641	-5.079*
LnFD	-2.782	-5.018*
LnTEI	-1.884	-5.809*
LnRET	-1.923	-4.712*
lnGG	-1.781	-4. 821*

Note: * indicates significance level at 1%.

The next step of the analysis, is to investigate cointegration between the ecological sustainability (lnLCF), financial development (lnFD), technological innovation (lnTEI), and renewable energy transition (lnRET) and green economic growth (lnGG). Prior to conducting the cointegration analysis, however, it is essential to assess slope homogeneity across the panel units. For this purpose, the study employs the slope homogeneity test developed by Pesaran and Yamagata [32]. The findings of the homogeneity test, presented in *Table 4*, reject the null hypothesis of slope homogeneity. This outcome indicates that the estimated coefficients are heterogeneous across countries, implying that the impacts of the explanatory variables differ among the sampled economies. Consequently, the presence of both CSD and slope heterogeneity necessitates the application of cointegration techniques capable of accommodating these panel characteristics.

Table 4. Results of slope homogeneity test.

	Statistic	P-Value
$\hat{\Delta}$	18.331*	0.000
$\hat{\Delta}_{\text{adj}}$	21.103*	0.000

Note: * indicates significance level at 1%.

The findings of the Westerlund panel cointegration test are presented in *Table 5*. The estimated statistics for both the group and panel cointegration tests provide sufficient evidence to reject the null hypothesis of no cointegration. This result indicates the existence of a stable long-run equilibrium relationship among the underlying variables, suggesting that they exhibit a common long-term movement over time.

Table 5. Results of westerlund cointegration test.

H0: No Cointegration	Value	Z-Value	P-Value
Group-t	-4.082***	-3.589	0.000
Group-a	-17.128***	0.581	0.728
Panel-t	--11.151***	-3.441	0.000
Panel-a	-20.205***	-2.086	0.016

Note: * and ** indicate significance levels at 1% and 5%, respectively.

Subsequently, the study proceeds to estimate the long-run relationships among the variables. Given that all variables are transformed into their logarithmic forms, the estimated long-run coefficients of FD, TEI, and RET and GG and the interaction term between RET and TEI (RET*TEI) can be interpreted as elasticities with respect to ecological sustainability LCF. The long-run estimation results obtained from the MG-CCE and MG-FMOLS panel estimation techniques are presented in *Table 5*.

Table 5. Mean group (panel) long run estimator results.

Variable	MG-CCE		MG-FMOLS	
	Coefficient	Prob.	Coefficient	Prob.
LnFD	0.4108*	0.000	0.3906*	0.001
LnTEI	0.3644*	0.000	0.3408*	0.000
LnRET	0.2809*	0.000	0.2518*	0.002
lnGG	0.2158*	0.000	0.1798*	0.000
Ln(RET×TEI)	0.008*	0.001	0.005*	0.003

Note: * indicates significance level at 1%, respectively.

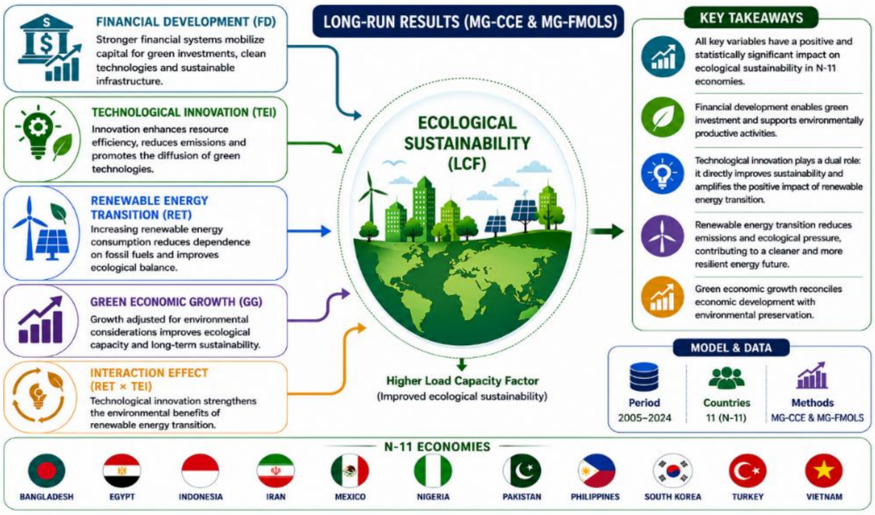
The long-run findings reveal that FD exerts a positive and statistically significant effect on ecological sustainability in the N-11 economies. This result suggests that the expansion of financial systems in these countries has gradually moved beyond merely financing conventional industrial growth and has begun to support environmentally productive activities. In economies such as South Korea, Turkey, Mexico, Indonesia, and Vietnam, deeper financial markets can facilitate access to capital for renewable energy projects, cleaner production technologies, and environmentally responsible infrastructure. From an economic perspective, this finding implies that FD improves the LCF by easing credit constraints, mobilizing investment resources, and enabling firms to adopt more efficient and less resource-intensive technologies. Therefore, in the N-11 context, FD appears to operate as an enabling mechanism for ecological transition rather than merely as a driver of energy-intensive expansion. This finding is consistent with Tamazian et al. [21] and Zaidi et al. [22], who argued that FD can improve environmental quality when financial resources are directed toward cleaner investment channels. However, it contrasts with Murshed et al. [23] and Nathaniel [24], who reported that financial expansion may intensify environmental degradation by stimulating fossil-fuel-based industrial activities. The difference may be explained by the growing orientation of several N-11 economies toward green finance, renewable energy investment, and sustainability-oriented development policies.

The positive coefficient of TEI indicates that innovation significantly enhances ecological sustainability in the N-11 economies. This result is economically meaningful because technological progress improves the efficiency with which energy, natural resources, and production inputs are used. In countries undergoing industrial upgrading, such as South Korea, Turkey, Mexico, and Vietnam, innovation can reduce ecological pressure by encouraging cleaner production, improving energy efficiency, and facilitating the diffusion of green technologies. For lower- and middle-income N-11 economies, TEI may also help overcome the traditional trade-off between economic growth and environmental protection by allowing production to expand with lower ecological costs. In this sense, innovation acts as a structural transformation channel through which economies can move from resource-intensive development toward knowledge-based and environmentally efficient growth. This result is in line with Han and Cai [4] and Demir et al. [8], who emphasized the environmental benefits of innovation and sustainable technologies. Nevertheless, it differs from [10] Ali et al. [10] and Su et al. [11], who found weak or insignificant environmental effects of TEI in some emerging economies. Such divergence may reflect differences in technological absorption capacity, innovation quality, and the extent to which innovation is directed toward green rather than purely production-expanding activities.

The results also show that RET positively affects ecological sustainability. This finding confirms that increasing the share of renewable energy in the energy mix improves the LCF in N-11 economies. Economically, this outcome is highly relevant because many of these countries have historically relied on fossil fuels to support industrialization, urban expansion, and export-oriented production. A shift toward renewable energy reduces pressure on ecological systems by lowering emissions, decreasing dependence on non-renewable energy sources, and improving the balance between biocapacity and ecological demand. In countries such as Turkey, Vietnam, Mexico, and South Korea, the expansion of renewable energy infrastructure has increasingly become part of broader strategies for energy security, industrial modernization, and climate resilience. The positive role of RET therefore reflects not only an environmental improvement but also a structural movement toward more sustainable growth. This finding supports the conclusions of Nathaniel and Khan [28], and Sahoo and Sethi [16], who documented the environmental benefits of renewable energy consumption. It also reinforces the argument that renewable energy is particularly important for emerging economies where rapid growth has traditionally been accompanied by high fossil-fuel dependence.

The coefficient of GG is also positive and significant, indicating that growth adjusted for environmental considerations contributes to ecological sustainability in the N-11 economies. This result suggests that when economic progress is accompanied by savings from natural resource preservation, lower particulate damage, and more sustainable investment patterns, it can improve rather than undermine environmental quality. In the N-11 countries, where development needs remain substantial, green growth provides a pathway for reconciling economic expansion with ecological resilience. This finding is particularly important because these economies cannot simply reduce growth ambitions; instead, they need to transform the composition and quality of growth. A positive effect of GG implies that environmentally adjusted growth mechanisms can strengthen biocapacity, reduce ecological pressure, and support long-term sustainability.

Most importantly, the interaction term between RET and TEI is positive and statistically significant. Although its coefficient is smaller than the direct effects, its significance carries important economic meaning. This result indicates that TEI strengthens the ecological effectiveness of RET in the N-11 economies. In practical terms, renewable energy alone may not be sufficient to generate strong environmental gains unless it is supported by innovation in storage systems, grid integration, energy efficiency, smart infrastructure, and clean industrial technologies. For many N-11 countries, RET still faces challenges such as intermittency, high installation costs, weak transmission networks, and limited technological capacity. TEI helps overcome these constraints by improving the efficiency, reliability, and affordability of renewable energy systems. Therefore, the positive interaction effect suggests a complementary relationship: renewable energy provides the clean energy foundation, while TEI enhances its productivity and ecological impact. In the context of N-11 economies, this result is particularly valuable because it shows that ecological sustainability requires not only replacing fossil fuels with renewables but also building the technological capacity needed to make RET more effective, scalable, and economically viable. Drawing upon the empirical findings obtained, a synthesized overview of the key results is visually presented in *Fig. 3* to provide a clearer and more integrated understanding of the relationships among the study variables.



Stronger financial systems mobilize capital for green investments, clean technologies and sustainable infrastructure.

Innovation enhances resource efficiency, reduces emissions and promotes the diffusion of green technologies.

Increasing renewable energy consumption reduces dependence on fossil fuels and improves ecological balance.

Growth adjusted for environmental considerations improves ecological capacity and long-term sustainability.

Technological innovation strengthens the environmental benefits of renewable energy transition.

All key variables have a positive and statistically significant impact on ecological sustainability in N-11 economies.

Financial development enables green investment and supports environmentally productive activities.

Technological innovation plays a dual role: it directly improves sustainability and amplifies the positive impact of renewable energy transition.

Renewable energy transition reduces emissions and ecological pressure, contributing to a cleaner and more resilient energy future.

Green economic growth reconciles economic development with environmental preservation.

Fig. 3. Schematic illustration of the long-run findings.

5 | Conclusion and Policy Recommendations

5.1 | Conclusion

Ecological sustainability has become an increasingly important concern for emerging economies due to the growing environmental consequences of rapid industrialization, urbanization, and fossil-fuel-based economic expansion. In this regard, the present study examined the effects of FD, TEI, RET, and green growth on ecological sustainability in the N-11 economies over the period 2005-2024. To achieve robust and reliable findings, the study employed advanced panel estimation techniques, including MG-CCE and MG-FMOLS estimators, which effectively account for CSD and slope heterogeneity among countries. The empirical findings reveal that FD contributes positively to ecological sustainability by facilitating environmentally productive investment, supporting green infrastructure, and improving access to cleaner technologies. Similarly, TEI significantly enhances ecological sustainability by promoting energy efficiency, cleaner production systems, and environmentally friendly technological transformation. The results further indicate that RET improves the LCF by reducing ecological pressure and decreasing dependence on fossil-fuel-based energy systems. In addition, GG was found to strengthen ecological sustainability through environmentally adjusted development pathways.

Most importantly, the interaction effect between RET and TEI was found to be positive and statistically significant. This result suggests that TEI substantially strengthens the environmental effectiveness of rene RET wable energy transition in the N-11 economies. In other words, renewable energy alone may not be sufficient to achieve strong ecological improvements unless it is accompanied by innovation-driven energy systems, cleaner technologies, advanced infrastructure, and efficient energy management mechanisms. Therefore, the findings emphasize that ecological sustainability in the N-11 countries depends not only on expanding renewable energy consumption but also on enhancing technological capabilities that can maximize the environmental benefits of RET.

5.2 | Policy Recommendations

The findings of this study provide several important policy implications for the N-11 economies. Policymakers should prioritize the development of integrated environmental strategies that simultaneously promote RET, TEI, and sustainable FD. Governments are encouraged to increase investment in green technological infrastructure, smart energy systems, renewable energy storage technologies, and environmentally friendly industrial innovation. In particular, the positive interaction effect between TEI and RET highlights the necessity of combining clean energy policies with innovation-oriented development strategies. Financial institutions should also expand green financing mechanisms and provide greater support for renewable energy projects and eco-innovation activities. Moreover, policymakers should strengthen institutional coordination, environmental regulations, and research and development incentives to accelerate sustainable energy transformation and ecological resilience across the N-11 economies. One limitation of this study is that it focuses only on N-11 economies, which may limit the generalizability of the findings to other regions. Additionally, the study relies on aggregate national-level indicators that may not fully capture sector-specific environmental dynamics. Future studies are encouraged to investigate the nonlinear and asymmetric effects of TEI and RET on ecological sustainability using more disaggregated data and alternative environmental indicators.

Authors' Contributions

J. M.: Writing-original draft, Methodology, Data Curation, Conceptualization, Software, and Visualization, and Validation. J. R. D. S.: Validation, Writing-Review & Editing, and Formal Analysis. M. P.: Writing-Review & Editing, Formal Analysis, and Investigation. The authors have read and agreed to the published version of the manuscript.

Data Availability

The data is available on request from the corresponding author.

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Conflict of Interest

There are no competing interests to declare.

Consent for Publication

The authors have given consent for the publication of this manuscript.

Ethics Approval and Consent to Participate

The authors confirm that this research did not involve human participants or animal subjects.

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