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RESEARCH ARTICLE

Technological Innovation, Economic Growth, and Environmental Sustainability: A Global Dynamic Panel Analysis

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Abstract
Technological innovation plays a crucial role in economic growth, but its environmental implications remain complex. This study examines the relationships among technological innovation, economic growth, and environmental sustainability using global panel data covering 1998–2024. Fixed-effects and two-step system generalized method of moments (GMM) estimators are employed to assess the effects of innovation indicators, foreign direct investment (FDI), research and development (R&D) expenditure, financial development, energy consumption, and trade openness on economic growth and carbon dioxide (CO_2) emissions. The findings reveal that economic growth, FDI, and patent applications are generally associated with increased emissions, highlighting the environmental costs of economic expansion. R&D expenditure reduces emissions in the individual dynamic specification but exhibits a negative short-run association with economic growth. High-technology exports are associated with lower emissions, although their growth effects remain inconsistent. Trade openness generally promotes economic growth while reducing emissions, whereas energy consumption significantly increases emissions without consistent growth benefits. These findings underscore the importance of promoting green innovation, sustainable FDI, renewable energy adoption, and environmentally responsible trade. The study highlights the need for coordinated policies that reconcile economic development with long-term environmental sustainability.

Keywords: Technological innovation; Economic growth; Environmental sustainability; CO_2 emissions; Dynamic panel analysis

1. Introduction

Technological innovation is widely recognized as a fundamental driver of economic growth, productivity enhancement, and sustainable development. Advances in industrial technologies, digitalization, and energy-efficient production systems have created opportunities for economic expansion while offering potential solutions to environmental challenges. However, technological progress can also intensify industrial activities, increase

energy consumption, and contribute to carbon dioxide (CO_2) emissions, particularly in economies heavily dependent on fossil fuels. Consequently, achieving economic growth without compromising environmental sustainability remains a major challenge for policymakers worldwide. Recent studies emphasize that the environmental consequences of technological innovation depend on the nature of technological advancement, energy sources, and institutional and economic conditions (Khan et al., 2024; Raihan et al., 2025a; Byaro & Timbuka, 2025).

The relationship between technological innovation, economic growth, and environmental sustainability is complex and multidimensional. Country-specific evidence has further highlighted the interrelationships among technological innovation, economic growth, energy consumption, and environmental sustainability, including studies focusing on Bangladesh, Vietnam, and Malaysia (Raihan, 2025; Raihan et al., 2024; Raihan et al., 2022). Technological advancement can improve resource efficiency, facilitate cleaner production, and accelerate the transition toward renewable energy. Nevertheless, innovation-driven industrial expansion may increase energy demand and environmental degradation when technological improvements are not accompanied by effective environmental policies. Research and development (R&D) expenditure is particularly important because it supports the development and commercialization of environmentally sustainable technologies. Recent empirical evidence highlights the potential contribution of R&D expenditure, energy efficiency, and green technological innovation to reducing carbon emissions (Khan et al., 2024; Amin et al., 2025; Wang et al., 2025). These findings suggest that technological innovation does not automatically generate environmental benefits; rather, its effectiveness depends on how innovation investments are directed and implemented.

Foreign direct investment (FDI), international trade, and financial development also influence the relationship between technological innovation and environmental sustainability. FDI can stimulate economic growth through capital accumulation, technology transfer, and productivity improvements, but investments in energy-intensive industries may increase carbon emissions. Similarly, trade openness can facilitate access to advanced technologies and international markets while potentially expanding carbon-intensive production. Financial development may support green innovation by improving access to investment capital, although its environmental implications depend on the allocation of financial resources. Recent studies demonstrate that these relationships vary across countries and economic structures, highlighting the importance of integrating innovation, investment, trade, and financial development into environmental policy frameworks (Khan et al., 2024; Altaf et al., 2025; Salam et al., 2025).

Despite the growing literature, important research gaps remain. Existing studies frequently focus on particular countries, regional groups, or individual innovation indicators, limiting understanding of how different dimensions of technological innovation interact with economic and environmental factors in a broader international context. For example, Khan et al. (2024) examined technological innovation, economic growth, and emissions in Belt and Road countries, while Amin et al. (2025) investigated R&D expenditure, green finance, and energy efficiency in BRICS economies. Furthermore, Byaro and Timbuka (2025) demonstrated that the relationship between green growth and environmental sustainability differs across income groups. These findings highlight the need for a broader assessment that simultaneously considers multiple innovation indicators and their relationships with economic growth and environmental quality.

Against this background, the present study investigates the relationships among technological innovation, economic growth, and environmental sustainability using global panel data covering 1998–2024. Specifically, it examines the roles of resident and non-resident patent applications, R&D expenditure, high-technology exports, and a composite innovation index, alongside FDI, financial development, energy consumption, and trade openness. The study employs fixed-effects estimation and two-step system generalized method of moments (GMM) models to account for country-specific heterogeneity, dynamic relationships, and potential endogeneity. By examining

economic growth and CO_2 emissions within a common empirical framework, the study contributes to the literature by providing a multidimensional assessment of innovation-related economic and environmental trade-offs. The findings offer policy-relevant insights into promoting green innovation, sustainable investment, energy efficiency, and environmentally responsible trade while supporting long-term economic development.

2. Literature review and theoretical framework

2.1. Technological innovation, economic growth, and environmental sustainability

Technological innovation is a key determinant of economic growth and environmental sustainability, although its effects vary across countries, industries, and technological capabilities. Innovation enhances productivity, facilitates industrial development, and improves resource efficiency, but it may also increase energy consumption and CO_2 emissions through expanded production activities. Khan et al. (2024), using dynamic panel estimators for 35 Belt and Road countries, found that technological innovation promotes economic growth and improves environmental quality, whereas economic expansion increases emissions. Similarly, Raihan et al. (2025a) emphasized the importance of innovation and green transitions in balancing economic development with environmental sustainability. Additional country-level studies have examined the contribution of technological innovation and renewable energy to environmental sustainability. Raihan (2025) investigated green energy and technological innovation in Bangladesh, while Raihan et al. (2024) examined the relationships among economic growth, energy, innovation, agriculture, forests, and CO_2 emissions in Vietnam. Similarly, Raihan et al. (2022) explored the relationships among economic growth, renewable energy consumption, technological innovation, and carbon emissions in Malaysia. These findings suggest that the environmental benefits of technological advancement depend on the adoption of cleaner production processes and supportive sustainability policies.

R&D expenditure plays an important role in technological progress by supporting innovation, knowledge creation, and the development of energy-efficient technologies. However, its economic and environmental effects may differ depending on investment priorities and the time required to commercialize innovations. Khan et al. (2024) demonstrated that R&D expenditure contributes to reducing carbon emissions, while Amin et al. (2025) found that R&D investment, green technological innovation, energy efficiency, and green finance improve environmental sustainability in BRICS economies. Similarly, Wang et al. (2025) highlighted the relationship between green technological innovation and firms' energy-consumption intensity. These findings indicate that targeted investment in environmentally sustainable technologies can help mitigate the environmental consequences of industrial development.

2.2. Foreign direct investment, trade openness, and financial development

FDI and international trade are important channels through which technological innovation influences economic growth and environmental quality. FDI can promote capital accumulation, technological diffusion, and industrial productivity, but its environmental consequences depend on the characteristics of investment activities. Khan et al. (2024) found that FDI stimulates economic growth while increasing carbon emissions, highlighting the potential environmental costs of foreign investment. The relationships between foreign investment, economic development, and environmental quality have also been investigated in individual-country contexts. Raihan et al. (2025b) examined the role of renewable energy and FDI in economic growth in Egypt, while Raihan et al. (2025c) analyzed the dynamic relationships among FDI, globalization, economic growth, energy consumption, and carbon emissions in Mexico. These studies provide additional perspectives on the potentially contrasting economic and environmental implications of international investment.

International trade can similarly enhance economic performance through market integration and technology transfer, although increased production and transportation may contribute to environmental degradation. Salam et al. (2025) examined the relationships among trade, financial development, and environmental outcomes in Belt and Road countries, reinforcing the importance of considering these factors jointly when evaluating sustainability. Financial development can influence environmental sustainability by facilitating investment in technological innovation, renewable energy, and cleaner production systems. However, financial resources may also support carbon-intensive industries, resulting in adverse environmental consequences. Altaf et al. (2025) examined the relationships among green finance, renewable energy, and environmental sustainability in OECD economies, while Amin et al. (2025) demonstrated the contribution of green finance to emissions reduction in BRICS economies. These findings underscore the importance of directing financial resources toward environmentally sustainable investments rather than assuming that financial development necessarily improves environmental quality.

2.3. Energy consumption and environmental sustainability

Energy consumption is a major determinant of environmental quality because fossil fuel dependence remains closely associated with CO_2 emissions. Although energy availability supports industrial production and economic activities, inefficient energy use can increase environmental degradation without generating proportional economic benefits. Amin et al. (2025) found that energy efficiency and green energy contribute to emissions reduction in BRICS economies. Related empirical research has investigated the role of energy composition, technological innovation, and economic growth in shaping emissions outcomes. Raihan et al. (2025d) examined energy sources, energy efficiency, technological innovation, and economic growth in relation to net-zero emissions in the United Kingdom. Matenda et al. (2024) similarly investigated the relationships among fossil and renewable energy consumption, technological innovation, globalization, economic growth, and CO_2 emissions in South Africa. Similarly, Byaro and Timbuka (2025) demonstrated that the environmental effects of green growth differ across income groups, suggesting that countries' development characteristics influence their ability to achieve sustainable economic expansion. These findings highlight the importance of renewable energy adoption, improved energy efficiency, and context-specific environmental policies in reducing the carbon intensity of economic development.

2.4. Theoretical framework

This study is grounded in Endogenous Growth Theory and the Environmental Kuznets Curve (EKC) hypothesis. Endogenous Growth Theory emphasizes the role of technological innovation, human capital, and R&D expenditure in promoting long-term economic growth (Romer, 1990; Aghion & Howitt, 1992). Within this framework, innovation improves productivity and production efficiency, while targeted technological development can facilitate the transition toward environmentally sustainable economic activities. However, the environmental consequences of innovation depend on whether technological progress supports cleaner production or expands carbon-intensive economic activities. Recent empirical findings by Khan et al. (2024) and Amin et al. (2025) support the relevance of technological innovation and R&D expenditure in understanding the relationship between economic development and environmental sustainability.

The EKC hypothesis proposes a nonlinear relationship between economic development and environmental degradation, suggesting that emissions may initially increase with economic expansion before declining as economies adopt cleaner technologies and stronger environmental regulations (Grossman & Krueger, 1995; Dinda, 2004). The applicability of the Environmental Kuznets Curve and Pollution Haven hypotheses has also been examined in developing-country contexts. Raihan (2023) investigated these theoretical relationships in Bangladesh, with particular attention to foreign direct investment and environmental outcomes. However, this relationship is

not universal and depends on technological capabilities, institutional quality, and economic structures. Byaro and Timbuka (2025) found that green growth reduces emissions in lower-middle-income economies but does not produce comparable reductions in higher-income groups within their sample. These findings emphasize the importance of country-specific conditions in shaping environmental outcomes. Accordingly, the present study integrates both theoretical perspectives to examine how technological innovation, FDI, financial development, energy consumption, and trade openness are associated with economic growth and CO_2 emissions. Although the EKC provides theoretical context, the study's empirical specifications do not directly test its nonlinear turning-point prediction.

2.5. Research gap and study contribution

Despite extensive empirical research, the relationships among technological innovation, economic growth, and environmental sustainability remain insufficiently understood across diverse economic contexts. Previous studies have primarily examined specific regions or economic groups, including Belt and Road countries (Khan et al., 2024), BRICS economies (Amin et al., 2025), and OECD economies (Altaf et al., 2025). Recent research has also examined the interactions among digital economic development, technological innovation, financial accessibility, and environmental sustainability in G-7 economies (Raihan et al., 2026). Furthermore, the environmental effects of innovation vary according to technological indicators, energy structures, and institutional conditions. Byaro and Timbuka (2025) also demonstrated the importance of income-level heterogeneity, indicating that findings from individual regions or country groups may not be universally applicable.

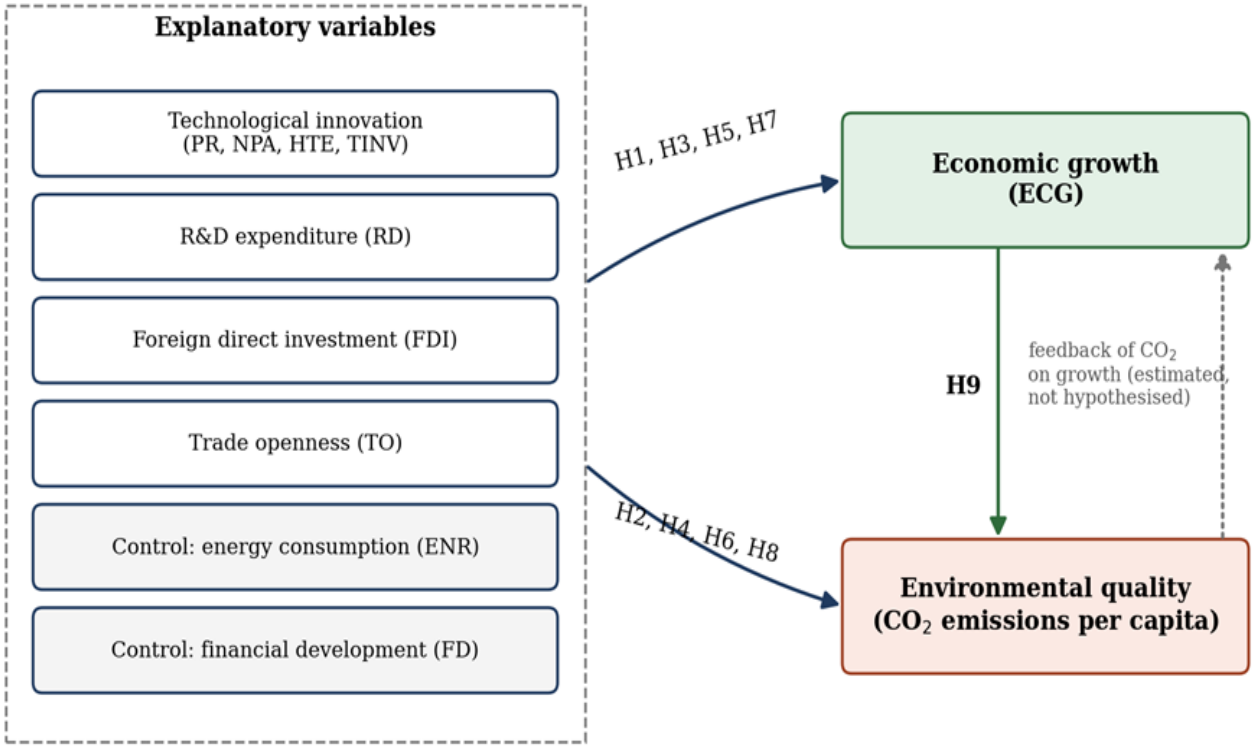


Figure 1. Conceptual framework illustrating the relationships among technological innovation, economic growth, and environmental sustainability.

To address these gaps, the present study examines the relationships among technological innovation, economic growth, and environmental sustainability using global panel data covering 1998–2024. Unlike studies focusing on individual innovation measures, it considers resident and non-resident patent applications, R&D expenditure, high-technology exports, and a composite innovation index, alongside FDI, financial development, energy consumption, and trade openness. By employing fixed-effects and two-step system generalized method of moments (GMM) estimators, the study provides a multidimensional assessment of the dynamic relationships between innovation, economic performance, and CO_2 emissions. Its contribution lies in comparing different innovation indicators within a common empirical framework and identifying policy-relevant economic and environmental trade-offs.

2.6. Research hypotheses and conceptual framework

Drawing on Endogenous Growth Theory, the EKC hypothesis, and the reviewed empirical literature, the study proposes nine hypotheses concerning the relationships among technological innovation, economic growth, and environmental sustainability. Specifically, technological innovation is expected to promote economic growth (H1) and reduce CO_2 emissions (H2), while FDI is hypothesized to increase both economic growth (H3) and emissions (H4). R&D expenditure is expected to enhance economic growth (H5) and reduce emissions (H6), whereas trade openness is hypothesized to promote economic growth (H7) and improve environmental quality by reducing emissions (H8). Finally, economic growth is expected to increase CO_2 emissions (H9), reflecting the environmental pressures associated with expanding economic activities.

The conceptual framework, presented in Figure 1, illustrates the proposed relationships between the explanatory variables and the two principal outcomes: economic growth and environmental quality, measured by CO_2 emissions per capita. Technological innovation, R&D expenditure, FDI, and trade openness are incorporated as explanatory factors, while financial development and energy consumption serve as control variables. Economic growth is additionally included in the emissions equation, and CO_2 emissions are included in the growth equation to examine their conditional relationship. This framework provides the theoretical foundation for the empirical models developed in the following section.

3. Methodology

3.1. Data sources and variables

This study examines the relationships among technological innovation, economic growth, and environmental sustainability using global panel data covering 1998–2024. The data were obtained from the World Development Indicators (WDI) database. Table 1 presents the variables and their measurements. The variables capture the principal economic, technological, financial, and energy-related factors influencing growth and environmental quality.

3.2. Model specification

Two complementary panel regression models are employed to examine the relationships among technological innovation, economic growth, and CO_2 emissions. The first model investigates the determinants of CO_2 emissions, while the second examines the factors associated with economic growth. Following the dynamic panel framework of Arellano and Bond (1991) and Blundell and Bond (1998), the models incorporate lagged dependent variables to account for persistence in economic and environmental outcomes.

The CO_2 emissions model is specified as follows:

$$CO_{2,it} = \alpha_0 + \rho CO_{2,i,t-1} + \beta_1 FDI_{it} + \beta_2 INN_{it} + \beta_3 ECG_{it} + \beta_4 FD_{it} + \beta_5 ENR_{it} + \beta_6 ITO_{it} + \mu_i + \varepsilon_{it} \quad (1)$$

The economic growth model is expressed as

$$ECG_{it} = \gamma_0 + \phi ECG_{i,t-1} + \gamma_1 FDI_{it} + \gamma_2 INN_{it} + \gamma_3 CO_{2,it} + \gamma_4 FD_{it} + \gamma_5 ENR_{it} + \gamma_6 ITO_{it} + \mu_i + \nu_{it} \quad (2)$$

Here, i denotes countries and t represents years. CO_2 indicates carbon dioxide emissions per capita, ECG represents economic growth, FDI denotes foreign direct investment, INN represents technological innovation, FD indicates financial development, ENR denotes energy consumption, and ITO represents international trade openness. The parameters ρ and ϕ capture the persistence of the respective dependent variables, while μ_i represents unobserved country-specific effects. The terms ε_{it} and ν_{it} denote the idiosyncratic error terms.

The models are estimated using alternative innovation indicators to assess their individual and combined relationships with economic growth and CO_2 emissions. Specifically, Models 1–4 incorporate PR, NPA, RD, and HTE individually; Model 5 includes the composite innovation index (TINV); and Model 6 incorporates all four individual innovation indicators simultaneously.

Table 1. Description and measurement of variables

Variable	Description and measurement	Symbol
CO_2 emissions	Carbon dioxide emissions (metric tons per capita)	CO_2
Economic growth	Annual GDP growth rate (%)	ECG
Foreign direct investment	FDI, net inflows (% of GDP)	FDI
Resident patent applications	Patent applications filed by residents	PR
Non-resident patent applications	Patent applications filed by non-residents	NPA
Research and development expenditure	R&D expenditure (% of GDP)	RD
High-technology exports	High-technology exports (% of manufactured exports)	HTE
Technological innovation index	Composite index constructed from PR, NPA, RD, and HTE	TINV
Financial development	Domestic credit to the private sector (% of GDP)	FD
Energy consumption	Energy use (kg of oil equivalent per capita)	ENR
International trade openness	Total trade as a percentage of GDP	ITO

3.3. Estimation techniques

The study employs fixed-effects estimation and two-step system generalized method of moments (GMM) estimation. Fixed-effects models control for time-invariant country-specific characteristics, while system GMM accounts for dynamic persistence and addresses potential endogeneity under appropriate instrument validity assumptions. The system GMM estimator combines equations in first differences and levels, using suitable lagged variables as instruments (Arellano & Bover, 1995; Blundell & Bond, 1998).

The two-step system GMM estimator is the primary estimation approach because the models include lagged dependent variables and potentially endogenous regressors. However, its reliability depends on the validity of the instruments and the underlying moment conditions. The Arellano–Bond second-order serial correlation test is used to assess serial correlation in the differenced residuals, while the Sargan overidentification test evaluates

instrument validity. A probability value greater than 0.05 for these tests is interpreted as a failure to reject the corresponding null hypothesis, although this does not establish instrument validity conclusively. Models that fail the diagnostic tests are interpreted cautiously (Roodman, 2009a, 2009b).

3.4. Regression analysis and interpretation

Regression coefficients are evaluated according to their direction, magnitude, and statistical significance at the 1%, 5%, and 10% levels. Positive coefficients indicate direct associations, whereas negative coefficients indicate inverse associations between explanatory and dependent variables. In the dynamic specifications, the estimated coefficients represent short-run relationships, while implied long-run effects can be calculated by dividing the relevant coefficient by one minus the coefficient of the lagged dependent variable, provided the dynamic process is stable.

The analysis compares the results across innovation indicators and estimation methods to assess the consistency of the relationships among technological innovation, economic growth, and environmental sustainability. Particular attention is given to the effects of economic growth on CO_2 emissions and the potentially contrasting economic and environmental implications of innovation, FDI, R&D expenditure, energy consumption, and trade openness. The estimated relationships are interpreted as conditional associations rather than definitive evidence of causality.

4. Results and discussion

4.1. Descriptive statistics

Table 2 presents the descriptive statistics for the variables included in the empirical analysis. The results reveal substantial variation in technological innovation, economic performance, financial development, energy consumption, and international trade across the sampled countries. Overall, the descriptive statistics demonstrate considerable cross-country heterogeneity, supporting the use of panel-data techniques that account for country-specific characteristics.

Table 2. Descriptive statistics

Variable	Mean	Std. Dev.	Minimum	Maximum
PR	10691.75	6078.21	1987.64	28933.22
NPA	4926.65	2120.49	1786.36	9163.31
RD	0.94	0.95	0.01	4.95
HTE	10.71	11.45	0.00	78.47
FDI	5.09	38.54	−1275.19	1282.63
ECG	1.84	6.01	−64.99	140.36
FD	38.90	35.27	0.00	304.58
MKT	52.18	50.48	0.01	352.156
ENR	2404.70	2951.90	9.55	28902.85
ITO	81.987	49.83	0.02	437.32

4.2. Correlation analysis

Table 3 reports the correlation matrix, providing preliminary insights into the relationships among the explanatory variables and economic and environmental outcomes. Resident patent applications are strongly positively

correlated with R&D expenditure (0.916) and non-resident patent applications (0.766), suggesting that countries with greater domestic innovation activity also tend to attract foreign patenting and invest more in research. CO_2 emissions are positively correlated with resident patents (0.758), non-resident patents (0.853), and R&D expenditure (0.816), indicating that innovation-intensive economies may also exhibit higher emissions.

Table 3. Correlation matrix

Variable	PR	NPA	RD	HTE	FDI	CO_2	ECG
PR	1.000						
NPA	0.766	1.000					
RD	0.916	0.661	1.000				
HTE	0.256	0.268	0.254	1.000			
FDI	−0.387	−0.239	−0.474	0.094	1.000		
CO_2	0.758	0.853	0.816	0.176	−0.364	1.000	
ECG	−0.169	−0.133	−0.260	−0.106	0.315	−0.246	1.000

4.3. Fixed-effects estimation of CO_2 emissions

Table 4 presents the fixed-effects estimates of the determinants of CO_2 emissions. The results reveal considerable heterogeneity across technological innovation indicators. Resident patent applications are positively and significantly associated with emissions, while non-resident patents exhibit a positive association in the individual specification but a negative association when innovation indicators are jointly included. R&D expenditure and high-technology exports are positively associated with emissions in their individual fixed-effects models. In contrast, the composite technological innovation index (TINV) has a negative and statistically significant coefficient, suggesting that broader innovation capacity may be associated with improved environmental performance. These contrasting findings indicate that the environmental implications of innovation depend on its measurement and composition.

Table 4. Fixed-effects estimation results for CO_2 emissions

Variable	M1	M2	M3	M4	M5	M6
FDI	4.300	−0.000	−0.000	−0.000	0.0170	−0.00133
PR	5.846***	—	—	—	—	1.360*
NPA	—	0.239***	—	—	—	−1.350**
RD	—	—	0.173**	—	—	0.100
HTE	—	—	—	0.097***	—	0.043***
TINV	—	—	—	—	−1.107***	—
ECG	0.006	0.000	0.034***	0.031***	0.0157	0.038***
FD	−0.002***	−0.002**	−0.003**	0.014***	0.645***	0.013***
ENR	0.000***	0.000***	0.000***	0.001***	0.0005***	0.001***
ITO	−0.002**	−0.002*	−0.017***	−0.012***	0.00111	−0.014***
Constant	3.412***	1.785***	5.660***	2.235***	4.710***	0.698
Observations	2242	2339	1318	819	96	519
R^2	0.246	0.270	0.276	0.409	0.720	0.588
Countries	116	120	117	119	18	87

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$

Economic growth is positively and significantly associated with CO_2 emissions in Models 3, 4, and 6, indicating that economic expansion remains linked to environmental pressures. Energy consumption is also positively associated with emissions across the reported specifications. Conversely, trade openness generally exhibits negative and significant coefficients, suggesting potential environmental benefits from international market integration. Financial development produces mixed results, with negative coefficients in Models 1–3 and positive coefficients in Models 4–6. These findings partly contrast with Khan et al. (2024), who reported environmental improvements associated with technological innovation, and are consistent with the broader observation by Byaro and Timbuka (2025) that environmental outcomes vary across economic contexts.

4.4. Dynamic panel estimation of CO_2 emissions

Table 5 presents the two-step system GMM estimates, which account for the persistence of emissions and potential endogeneity. The lagged CO_2 coefficient is positive and highly significant across all specifications, ranging from 0.926 to 0.976, indicating substantial persistence in emissions.

The innovation indicators exhibit different environmental effects. Resident and non-resident patent applications are positively associated with emissions, whereas R&D expenditure (−0.056, $p < 0.01$) and high-technology exports (−0.011, $p < 0.01$) are negatively associated with emissions in their individual specifications. The negative R&D coefficient is consistent with Khan et al. (2024) and Amin et al. (2025), who identified the environmental benefits of research investment and green innovation. However, the positive R&D coefficient in the combined specification suggests that the relationship is sensitive to model composition. The innovation index is statistically insignificant in the dynamic model, indicating that the negative fixed-effects association is not robust across estimators.

Table 5. Two-step system GMM results for CO_2 emissions

Variable	M1	M2	M3	M4	M5	M6
FDI	0.000**	0.000***	0.000***	0.001***	0.0170	0.000***
PR	2.620**	—	—	—	—	0.958***
NPA	—	0.016***	—	—	—	0.000***
RD	—	—	−0.056***	—	—	0.958***
HTE	—	—	—	−0.011***	—	0.000***
TINV	—	—	—	—	0.098	—
ECG	0.029***	0.025***	0.030***	0.032***	0.034***	0.044***
FD	−0.000***	−0.000***	−0.000***	−0.001***	0.011	−0.000
ENR	4.180***	4.430***	6.620***	4.360***	0.000	4.130***
ITO	−0.000***	−4.070	−0.000***	−0.000***	−0.001*	−0.000***
Lagged CO_2	0.976***	0.976***	0.976***	0.965***	0.926***	0.958***
Constant	−0.007	−0.102***	−0.077***	0.061***	0.133	0.027
Observations	2200	2294	1318	819	96	519
Countries	116	120	117	119	18	87
AR(2) p-value	0.246	0.217	0.219	0.504	0.528	0.285
Sargan p-value	0.800	0.941	0.820	0.859	0.952	0.841

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$

Economic growth remains positively and significantly associated with CO_2 emissions in all six models. In Model 1, the coefficient of 0.029 indicates that a one-percentage-point increase in GDP growth is associated with an additional 0.029 metric tons of CO_2 per capita in the short run, holding other included variables constant. FDI is also positively associated with emissions in most specifications, while trade openness generally exhibits negative coefficients. Energy consumption remains positively associated with emissions, except in the innovation-index specification, where its coefficient is reported as insignificant. These results support the findings of Khan et al. (2024) and Amin et al. (2025), who similarly identified economic expansion as an important source of environmental pressure.

4.5. Fixed-effects estimation of economic growth

Table 6 reports the fixed-effects estimates for economic growth. FDI has a positive and statistically significant coefficient in Models 1–4, indicating that foreign investment is generally associated with improved economic performance. Non-resident patent applications are positively associated with growth in Model 2, while the composite innovation index exhibits a weak positive association in Model 5. In contrast, resident patent applications are statistically insignificant, suggesting that domestic patenting does not consistently translate into immediate economic gains. R&D expenditure has a negative and statistically significant coefficient in Models 3 and 6, potentially reflecting the delayed commercialization of research outcomes and the short-term costs of innovation investment. High-technology exports are insignificant in their individual specification but weakly positive in the combined model. Financial development generally exhibits negative coefficients, whereas trade openness is positively and significantly associated with growth across all six specifications. Energy consumption produces mixed results, suggesting that its economic contribution depends on the efficiency and structure of energy use. The positive relationship between FDI, trade openness, and economic growth, together with the negative financial-development coefficient, is broadly consistent with Khan et al. (2024). Furthermore, Raihan (2024) examined the influences of FDI and carbon emissions on economic growth, providing a relevant comparative context for interpreting the economic and environmental dimensions of foreign investment.

Table 6. Fixed-effects estimation results for economic growth

Variable	M1	M2	M3	M4	M5	M6
FDI	0.013**	0.011*	0.011**	0.014**	0.189	0.005
PR	−3.580	—	—	—	—	−5.460
NPA	—	0.245**	—	—	—	5.160
RD	—	—	−0.704**	—	—	−2.490**
HTE	—	—	—	−0.217	—	0.099*
TINV	—	—	—	—	3.270*	—
CO_2	0.135	0.017	0.652***	1.356***	—	—
FD	−0.022***	−0.022***	−0.042***	−0.086***	—	−0.046***
ENR	−0.0002	−0.000	−0.000	−0.001**	−0.001	0.001**
ITO	0.040***	0.040***	0.059***	0.104***	0.201***	0.086***
Constant	0.291	−0.826	−3.721***	−6.198***	−21.70**	−6.195*
Observations	2242	2339	1318	819	96	519
R^2	0.033	0.036	0.107	0.176	0.202	0.116
Countries	116	120	117	119	18	87

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$

4.6. Dynamic panel estimation of economic growth

Table 7 presents the two-step system GMM estimates for economic growth. The results indicate that the effects of innovation and other economic factors vary across specifications. However, the diagnostic tests show that only Models 1 and 3 satisfy both the AR(2) and Sargan tests at the 5% significance level. Consequently, these models provide the principal basis for interpreting the dynamic growth relationships.

In Model 1, resident patent applications are positively associated with economic growth, although the relationship is significant only at the 10% level. FDI (0.004, $p < 0.01$) and trade openness (0.007, $p < 0.01$) exhibit positive and statistically significant coefficients, suggesting that international investment and market integration contribute to economic performance. Conversely, financial development is negatively associated with growth. These findings are broadly consistent with Khan et al. (2024), who reported positive growth associations for technological innovation, FDI, and international trade but a negative association for financial development.

Model 3 reveals a negative and statistically significant coefficient for R&D expenditure (−0.123, $p < 0.01$), indicating an adverse short-run association with economic growth. This result may reflect the time required for research investment to generate commercially productive innovations. CO_2 emissions also exhibit a negative coefficient (−0.023, $p < 0.05$), suggesting that environmental degradation may be associated with reduced economic performance after controlling for other factors. The findings emphasize the importance of integrating environmental objectives into innovation strategies rather than evaluating technological investment solely through its immediate growth effects.

Table 7. Two-step system GMM estimation results for economic growth

Variable	M1	M2	M3	M4	M5	M6
Lagged ECG	0.422***	−1.913***	0.360***	−0.001	−0.173	0.220***
FDI	0.004***	0.006***	0.005***	−0.001	0.494	−0.005***
PR	5.680*	—	—	—	—	4.540**
NPA	—	0.185***	—	—	—	2.800
RD	—	—	−0.123***	—	—	−0.438***
HTE	—	—	—	0.0002	—	0.045***
TINV	—	—	—	—	−0.173	—
CO_2	−0.0232	1.850***	−0.023**	−0.024**	0.494	—
FD	−0.012***	−0.008***	−0.019***	−0.0002	—	−0.018***
ENR	−1.070	1.620	−2.390	−0.0002	−0.00231*	−6.890***
ITO	0.007***	0.008***	0.006***	0.0002	−0.0415	0.004***
Constant	1.559***	1.439***	2.550***	−0.0001	0.0390	2.444***
Observations	2193	2294	1315	819	96	519
Countries	116	120	117	119	18	87
AR(2) p-value	0.155	0.000	0.172	0.931	0.045	0.002
Sargan p-value	0.313	0.000	0.195	0.000	0.596	0.707

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$

4.7. Direction, magnitude, and significance of the key relationships

Table 8 summarizes the principal relationships obtained from the system GMM specifications that satisfy the reported diagnostic tests. Economic growth exhibits a positive and statistically significant association with CO_2

emissions, with a short-run coefficient of 0.029 in the emissions equation. The corresponding implied long-run coefficient is approximately 1.21. R&D expenditure is negatively associated with both CO_2 emissions (−0.056) and short-run economic growth (−0.123). These findings suggest a potential trade-off between immediate economic performance and environmental improvement. FDI and trade openness exhibit positive growth associations, while FDI is also positively associated with emissions. Trade openness generally exhibits a negative relationship with emissions, although the coefficients are too small at the reported precision to quantify their economic magnitude reliably. Financial development and CO_2 emissions are negatively associated with economic growth in the diagnostically acceptable models.

Table 8. Direction, magnitude, and significance of key relationships (system GMM)

Relationship	Table–Model	Direction	Short-run coefficient	Implied long-run effect
ECG → CO_2	5–1	Positive	0.029***	≈ 1.21
RD → CO_2	5–3	Negative	−0.056***	≈ −2.33
FDI → CO_2	5–1	Positive	0.000**	Not computable
ITO → CO_2	5–1	Negative	−0.000***	Not computable
FDI → ECG	7–1	Positive	0.004***	≈ 0.007
ITO → ECG	7–1	Positive	0.007***	≈ 0.012
RD → ECG	7–3	Negative	−0.123***	≈ −0.192
CO_2 → ECG	7–3	Negative	−0.023**	≈ −0.036
FD → ECG	7–1	Negative	−0.012***	≈ −0.021

Note: *** $p < 0.01$; ** $p < 0.05$

These findings reinforce the importance of distinguishing between economic expansion and environmentally sustainable development. Khan et al. (2024) similarly identified the environmental costs of growth and FDI, while Amin et al. (2025) reported that R&D expenditure and energy efficiency contribute to emissions reduction. Byaro and Timbuka (2025) further demonstrated that environmental outcomes differ across income groups, emphasizing the need for policies that account for economic and institutional heterogeneity.

4.8. Hypothesis testing

Table 9 summarizes the evidence for the nine research hypotheses. The findings provide weak support for the hypothesis that technological innovation promotes economic growth (H1), as resident patent applications exhibit a weak positive association in the diagnostically acceptable dynamic model. However, the hypothesis that technological innovation consistently reduces CO_2 emissions (H2) is not supported because the environmental effects vary across innovation indicators and estimation methods.

The results support the positive association of FDI with economic growth (H3) and emissions (H4). The hypothesis that R&D expenditure promotes economic growth (H5) is rejected because the estimated short-run relationship is negative and statistically significant. Conversely, the negative association between R&D expenditure and emissions provides partial support for H6, although the fixed-effects results differ from the dynamic estimates. Trade openness is positively associated with economic growth (H7) and generally negatively associated with emissions (H8). Finally, the consistently positive relationship between economic growth and CO_2 emissions supports H9.

Table 9. Summary of hypothesis testing

Hypothesis	Empirical evidence	Result
H1: Innovation → ECG (+)	PR weakly positive in valid GMM; NPA and TINV positive in selected FE models	Weak support
H2: Innovation → CO_2 (−)	PR and NPA positive; HTE negative in individual GMM; TINV insignificant in GMM	Not supported
H3: FDI → ECG (+)	Positive in FE Models 1–4 and valid GMM Models 1 and 3	Supported
H4: FDI → CO_2 (+)	Positive in most GMM specifications; generally insignificant in FE	Supported in GMM
H5: RD → ECG (+)	Negative and significant in FE and GMM	Rejected
H6: RD → CO_2 (−)	Negative in individual GMM; positive in individual FE	Partial support
H7: ITO → ECG (+)	Positive in all FE and valid GMM models	Supported
H8: ITO → CO_2 (−)	Negative in most FE and GMM models	Supported
H9: ECG → CO_2 (+)	Positive and significant in all emissions GMM models	Supported

4.9. Discussion and policy implications

The empirical findings highlight the complex relationship between technological innovation, economic growth, and environmental sustainability. Although technological innovation can support economic expansion, its environmental consequences depend on the characteristics of innovation activities. Patent applications are generally associated with increased emissions, whereas R&D expenditure and high-technology exports exhibit emissions-reducing associations in their individual dynamic specifications. These findings suggest that innovation policies should prioritize environmentally sustainable technologies rather than technological expansion alone. The results are consistent with Amin et al. (2025), who emphasized the contributions of green innovation, R&D expenditure, and energy efficiency to environmental sustainability in BRICS economies. The importance of integrating technological innovation, renewable energy, and environmental objectives is also reflected in country-level research on India, Malaysia, and South Africa (Raihan & Voumik, 2022; Raihan et al., 2022; Matenda et al., 2024). These studies reinforce the relevance of considering national energy structures and economic conditions when designing policies to promote sustainable technological development.

The positive associations of FDI and trade openness with economic growth demonstrate the importance of international economic integration. However, the positive relationship between FDI and emissions indicates that investment promotion should be accompanied by environmental safeguards and incentives for low-carbon industries. Trade openness, by contrast, generally exhibits favorable economic and environmental associations, suggesting that international trade may facilitate technological diffusion and improved production efficiency. These findings support the need for coordinated investment and trade policies that promote cleaner technologies and sustainable industrial development.

The positive relationship between economic growth and CO_2 emissions, together with the strong emissions persistence observed in the dynamic models, suggests that economic expansion remains closely linked to environmental pressures in the sampled countries. Energy consumption is also positively associated with emissions, emphasizing the importance of improving energy efficiency and reducing dependence on fossil fuels. Recent evidence from Byaro and Timbuka (2025) indicates that the environmental effects of green growth differ across income groups, suggesting that sustainability policies should reflect national economic structures and technological capabilities.

Overall, the results suggest that achieving sustainable economic development requires coordinated policies promoting green R&D, renewable energy, environmentally responsible FDI, and trade in cleaner technologies. However, these policy implications should be interpreted in light of the study's limitations. The unbalanced panel, variation in country coverage across specifications, potential multicollinearity, and incomplete reporting of GMM instrument diagnostics constrain the generalizability and causal interpretation of the estimates. Future research should examine income-group heterogeneity, distinguish green from conventional innovation, and strengthen the robustness of dynamic panel estimation.

5. Conclusion

This study examined the dynamic relationships among technological innovation, economic growth, and environmental sustainability using global panel data covering 1998–2024. Employing fixed-effects models and two-step system generalized method of moments (GMM) estimators, the analysis assessed the roles of technological innovation, FDI, R&D expenditure, financial development, energy consumption, and trade openness in shaping economic growth and CO_2 emissions. The findings reveal that technological innovation has heterogeneous economic and environmental effects. Resident and non-resident patent applications are generally positively associated with economic growth and CO_2 emissions, although their significance varies across model specifications. R&D expenditure is negatively associated with economic growth in the short run but contributes to reducing emissions in the individual dynamic specification, highlighting potential trade-offs between immediate economic performance and environmental sustainability. High-technology exports are associated with lower emissions in the individual dynamic model, while their contribution to economic growth remains less consistent. Furthermore, FDI generally promotes economic growth but is also associated with increased emissions, whereas trade openness supports economic performance and is generally associated with improved environmental quality. Energy consumption significantly increases emissions without demonstrating consistent economic growth benefits. Importantly, the results indicate that economic growth remains positively and significantly associated with CO_2 emissions, suggesting that economic expansion has not been effectively decoupled from environmental degradation across the sampled economies. These findings underscore the importance of integrating environmental considerations into technological innovation and economic development strategies. Policymakers should prioritize investments in green technologies, renewable energy, and energy-efficient production systems while promoting environmentally responsible FDI, sustainable trade, and targeted R&D expenditure. Such measures can help reconcile economic development objectives with long-term environmental sustainability.

Nevertheless, the findings should be interpreted cautiously because of cross-country heterogeneity, differences in sample coverage, and diagnostic limitations in some dynamic model specifications. Future research should examine differences across income groups and regions, distinguish between green and conventional technological innovation, and investigate sector-specific technological pathways to provide more targeted policy recommendations. Overall, the study emphasizes that technological advancement alone is insufficient to ensure environmental sustainability; its benefits depend on effective policy coordination, sustainable investment priorities, and the transition toward low-carbon economic development.

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