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How environmental patents, education, and energy transition impact greenhouse gases: evidence from E7 countries

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Mitigating greenhouse gas emissions (GHG) is crucial to achieving sustainable development and ensuring a prosperous and environmentally sound future. This study is motivated by the pressing need to address the environmental challenges faced by the E–7 economies—Brazil, India, Indonesia, Russia, Mexico, China, and Turkey—due to their rapid economic transitions and significant contributions to global GHG emissions. It investigates the long-term impact of environmental patents (ENP), financial development (FD), energy transition (ENT), and education (EDU) on GHG in the E–7 nations using second-generation econometric methods, including momentum quantile regression (MMQR), over the period 1990–2019. It also investigates the moderating effects of FD on ENT and EDU in influencing GHG emissions. The results reveal that ENT and ENP reduce GHG emissions across all quantiles, with ENT's effect stronger at lower quantiles and ENP's influence intensifying at higher quantiles. EDU shows a consistent positive impact on GHG across quantiles, reflecting its role in driving industrialization and energy demand, while FD reduces GHG emissions significantly at higher quantiles, supporting its role in green investments. Interaction terms indicate that FD enhances the impact of ENT in reducing GHG emissions but moderates EDU's effect in a way that can either amplify or offset emissions depending on the context. The robustness analysis validates these findings, particularly for ENT and FD, and highlights EDU's potential for emissions reduction under specific conditions. These findings emphasize the need for targeted policies that leverage ENT and ENP for emissions reduction, strategically direct FD toward sustainable investments, and manage the dual role of EDU in emissions dynamics. This study offers critical insights for policymakers in the E–7 nations to balance economic growth with environmental sustainability, contributing to global efforts to combat climate change.

KEYWORDS
environmental patents, greenhouse gas, energy transition, financial development, MMQR

1 Introduction

For the sake of promoting healthy environments and sustainable development, the energy transition (ENT) and decreasing greenhouse gas emissions (GHG) are essential (Avagyan, 2021). During the Paris Agreement, 196 countries emphasized the significance of maintaining the rise in universal temperature to greatly under 2°. This calls for significant cuts in GHG, with net-zero emissions. To meet these goals, there must be a move to cleaner energy sources, like renewable energy (RE) (Wang et al., 2022). Additionally, lowering GHG has numerous additional advantages, such as bettering water and air quality, improving human health, and saving biodiversity. Hence, making investments in the ENT and lowering GHG is essential not only for reducing the negative impacts of the environment but also for advancing sustainable progress and raising the standard of living for all people worldwide (Qing et al., 2023). The Sustainable Development Goals (SDGs) have become a ray of confidence in addressing environmental confronts (Aydin, 2014). According to Ullah et al. (2023), these goals offer a thorough roadmap for addressing the plethora of problems related to climate change and ENT.

It is crucial to understand that the adverse effects of climate change are not only felt by emerging countries, but also by the richest nations in the world, including the Emerging Seven (E−7), which are Brazil, India, Indonesia, Russia, Mexico, China, and Turkey. Unquestionably, it the important to develop a policy framework to address ecological and environmental problems to achieve environmental objectives. About 45% of the CO_2 produced worldwide comes from these countries. According to Husnain et al., 2022, the top four emitters of carbon dioxide are Indonesia, China, India, and Russia. The importance of energy requirements in the E7 nations has been caused by continued high GDP, which has resulted in climatic and ecological unevenness (Gyamfi et al., 2021). Moreover, E7 nations are characterized as developing economies undergoing rapid structural economic transformations, particularly during the 1990–2019 period. This transformation has been associated with significant industrial development (Zafar and Khan, 2024), which often results in increased carbon emissions and environmental degradation (Oluc et al., 2024). These structural changes have led to trade-offs between economic growth and environmental sustainability, highlighting the urgent need for E7 countries to adopt sustainable development practices to mitigate negative environmental impacts.

The E7 nations have increased their expenditures in green technology and RE over the past few decades to lower CO_2 emissions. Investments in green technology and RE have increased by over 38 percent and 42% in China and India, respectively, and by more than 16% and 30% in all emerging nations. The median annual growth in GDP of the E7 countries will be more than twice that of the members of the G7 by 2050. According to the report, the G7 countries' share of the global economy will fall to 20% by 2050, while the E7 countries will make up half of it in terms of GDP levels. To support the sustainable development of seven emerging market economies, it is important theoretically and practically to study the relationship between the consumption of RE, environmental patents, education, and environmental pollution.

For all nations to support a sustainable future, GHG must be reduced, and the ENT be improved (Avagyan, 2021; Chien et al., 2022). But for this to happen, important policy steps must be taken by decision-makers. As the world quickly moves toward digitalization (Abbas and Sheikh Sheikh, 2024), environmental patents (ENP) are essential areas of policy and research development. The use of ENP like energy-efficient buildings, smart grids, and RE knowledge has arisen as a hopeful route for dropping GHG (Shahbaz et al., 2022). The use of ENP inventions also presents a chance to enhance ecological management and monitoring, which will lead to better green resourcefulness (Li et al., 2023). ENP advancements can improve one-side executive policies by giving users the tools they need to aggressively control their energy use and cut waste, thus furthering energy productivity (Tzeremes et al., 2023). Since this connection provides avenues for discussing environmental issues and achieving sustainable development objectives, research into the ENP nexus concerning ENT and GHG has become crucial to ensure a sustainable future.

Investment prospects for RE, energy-efficient expertise, and financial development (FD) can similarly play a crucial role in accelerating the move to a low-carbon country (Liu et al., 2023; Shair et al., 2024). By encouraging sustainable investing, ENT policies can also have a noteworthy impact on the direction of FD (Kazim and Rafique, 2023; Ullah et al., 2022). Li et al. (2023) backed up the importance of FD for a sustainable potential and argued that it can make it easier to implement regulations that encourage the decline of GHG. Additionally, it helps in the development of jobs in the RE industry, fostering economic expansion and lowering greenhouse gas emissions at the same time. To ensure an equitable and environmentally friendly future, the effects of education and human development (HD) must be considered as the world transitions to an emission-free economy (Li et al., 2023). Education helps people embrace sustainable traditions, learn new skills, and innovate in the development and deployment of RE sources (Hassan, Gull, and Farasat, 2023; Sezgin et al., 2021). Understanding this connection better can advance sustainable growth and ensure equitable ENT (Adekoya et al., 2021). If poorly managed, the ENT can lead to unemployment in specific industries (Ramzan et al., 2023). GHG and environmental problems also extremely affect populations (Chien et al., 2022). E−7 economies are approaching net-zero and RE goals. ENP, FD, and education are expected to accelerate ENT and lower GHG in the future.

This research examines how ENP, education, and FD affect ENT and GHG in the E−7 economies during 1990–2019. This study may help the E−7 nations achieve SDGs by bolstering the ENT and improving climatic quality. First, most studies examine how technological inventions affect RE and climatic quality. However, not all inventions are precisely related to RE and climatic issues. ENP may be a better predictor of the shift to RE and climatic quality. This study fills a significant gap in the literature by empirically examining the effects of ENP on ENT and climatic quality.

Second, this study shows how FD interacts with ENP and EDU to affect ENT and the environment. The work also investigates all these components simultaneously using E−7 data. A few recent studies have examined the impact of ENP on the environment in E−7 nations. Finally, due to globalization, economies are more interdependent economically, socially, and politically. The study uses second-generation methods that account for cross-sectional dependency (CD). Traditional panel data methods cannot capture the CD among the panel. In a world striving for sustainability, our study findings are valuable. The study adds to environmental economics literature, helping policymakers and researchers create a greener world.

2 Literature review

2.1 Energy shift and its factors

Climate change and global warming have caused flooding, wildfires, extreme weather, droughts, and desertification in developing and developed nations. The Paris Agreement, COP 26, and COP 27 show that several countries have collaborated to solve this problem. Policymakers, scholars, and governments suggested switching to a sustainable energy economy. Thus, the ENT is a feasible solution to universal warming and environmental change. Sustainable energy is recommended to combat climate change. The drivers of the ENT have recently been highlighted in several empirical studies, including FD (Liu et al., 2023), digitalization (Shahbaz et al., 2022; Tzeremes et al., 2023), power (Chien et al., 2022), technological advancement (Onifade and Alola, 2022), and ecological regulations (Yuan et al., 2022). Due to the characteristics of the country under study, the length of the investigation, and the econometric techniques used, the results developing from these findings produced uncertain results.

Rahman and Velayutham (2020) examined ENT factors using panel instruments like DOLS and FMOLS to suggest SGDs in South Asian countries from 1990 to 2014. Economic advancement, gross creation of wealth, energy, and the ENT were linked positively in the study. GDP and the creation of gross capital advance ENT in the sample. Liu et al. (2023) used 2000–2020 G-7 data to show that FD promotes RE. From 2000 to 2015 in China, Fan and Hao (2020) examined ENT drivers. This association is investigated using Granger causality and VECM. The findings showed that FDI and GDP cause ENT in China, indicating that changing the selected variables will significantly affect ENT in China. Like this, Li et al. (2023) claimed that ICT, R&D, and HD are important causes of the rising clean energy in China. Governance and environmental laws are major driving forces behind China's ENT (Yuan et al., 2022). Shahbaz et al. (2022) also supported the idea that digitalization significantly and favorably influenced the growth of clean energy in 72 nations. Likewise, Tzeremes et al. (2023) asserted that ICT growth is a key driver of the BRICS countries' promotion of the ENT.

Wen et al. (2022) examined ENT drivers from 1995 to 2017 using panel techniques to propose an environmentally friendly approach for 79 economies. Eco-innovation, social advancement, and financial stability help ENT, but GDP does not. Wang et al. (2021) used panel approaches to examine economic progress toward ENT in European nations from 1985 to 2018. Coal and natural gas prices can describe ENT demand alongside real GDP. Three explanatory factors cause the ENT over time. Short-term causality links the ENT to fossil fuel prices. These findings demonstrate the importance of GDP and fossil fuel pricing in the ENT. Onifade and Alola (2022) projected the beneficial and substantial impact of environmental advances in technology on ENT for 1992–2018 in emerging seven economies. Wang et al. (2022) found ENT-growth linkages by seeing OECD nations' risks like political, economic, and financial. Rennet panel estimators and 1997–2015 data revealed the association. Financial and economic thresholds separate ENT and economic development. ENT boosts GDP only when the first threshold is crossed. When economic and economic risks are below the threshold levels, the ENT has little negative impact on economic development.

2.2 Greenhouse gas and its factors

Human activity raises the global temperature. This makes the greenhouse effect a danger to human life rather than an ally. Coastal towns flood, agricultural areas dry, storms increase, and glaciers melt. Countries consume energy for GDP. If dirty, this energy boosts GDP and environmental degradation. Thus, GDP and environmental degradation must be balanced. Many factors contribute to ecological damage from GHG. Research on the factors of GHG has taken over the environment and energy field, but findings have been inconclusive due to the study country, the time frame, and the econometric methods. Hassan et al. (2022) examined GHG drivers in China from 1987 to 2019 to determine how energy efficiency reduces GHG emissions. Through extensive empirical analysis and innovative empirical techniques, the researchers presented the relationship between the variables. Green energy investment strongly correlates with GHG emissions, supporting ecological integrity. Natural resources and economic policy uncertainty boost GDP but harm ecological sustainability. In their study on the drivers of GHG, Chien et al. (2022) used data from 1995 to 2018 for ten Asian States and the CS-ARDL. The findings showed that RE and growth squared both helped to reduce greenhouse gas emissions. On the other hand, urbanization and economic development led to an increase in GHG over the long and medium term. Additionally, the complete analysis by CCEMG and AMG discovered that alternate energy and gross domestic product are decreasing GHG when compared to GDP and urbanization. 73 emerging countries were studied between 1990 and 2016 by Jahangir et al. (2022) to determine the importance of getting environmental sustainability to demonstrate a correlation between economic and environmental wellbeing. The overall results suggested that technological developments support the reduction of GHG. Furthermore, it is established that technological advancements moderate the negative ecological effects associated with the exploitation of natural resources. It was eventually learned that GHG levels dropped with economic and HD. Ullah et al. (2022) made a similar case for the OECD panel, contending that increased FD and globalization contribute to GHG reduction. Ramzan et al. (2023) study for the greenest economies used quarterly data from 1994 to 2019 and a quantile-causality approach.

The study's goal was to evaluate how well new technological advancements could predict environmental quality. By harming CO_2 emission, the results showed that technological innovation has substantial predictive power in advancing environmental quality.

Studies (Abbasi et al., 2022a; Abbasi et al., 2022b) used the ARDL methods to discover the causes influencing the GHG in Pakistan. According to the research, both financial and economic development in the long and short terms increase GHG emissions. Long-term technological progress and HD also result in a significant decline in GHG. Finally, the causality test validates a strong causal relationship between GHG and its drivers.

The findings suggest that Pakistan should develop energy technologies to achieve SDGs 7 & 13. According to Appiah-Otoo et al. (2022), ICT reduces CO_2 emissions in countries in 110 countries. Qing et al. (2023) examined the implications of energy for GHG in the context of the BRICS using data spanning from 200 to 2019. The effect of political risk and GDP on GHG related to energy is also covered in this study. To obtain the results, moment quantile regression was used. The study shows that GDP raises energy-related GHG emissions. However, energy-related GHG is reduced using efficient energy use and RE. Political risk also reduces GHG emissions associated with the energy sector. In addition, numerous other works (Chien et al., 2022; Li et al., 2023; Onifade and Alola, 2022) used various samples, periods, and estimation techniques to empirically demonstrate the implication of various aspects such as FD, technology, HD, energy usage, and growth in the economy influencing the GHG.

2.3 Research gap

The current study addresses several critical research gaps in the literature on greenhouse gas emissions and environmental sustainability, particularly within the context of the E−7 economies. Despite the increasing focus on climate change mitigation, limited research has explored the combined and nuanced effects of energy transition, environmental patents, financial development, and education on GHG emissions in emerging economies undergoing rapid economic transitions. Most existing studies either focus on developed economies or analyze these variables in isolation, leaving a gap in understanding their interconnected dynamics in the E−7 nations.

First, while previous studies have highlighted the role of ENT and ENP in reducing GHG emissions, the differential impacts of these factors across varying levels of emissions have been largely overlooked. This study bridges this gap by employing the momentum quantile regression (MMQR) approach, which provides a detailed examination of how ENT and ENP influence GHG emissions across different quantiles, capturing their varying effectiveness in low- and high-emission scenarios.

Second, the role of EDU in driving emissions remains ambiguous in the literature, as it can simultaneously contribute to industrial expansion and promote environmentally conscious behavior. Existing research has yet to explore the dual nature of education in transitional economies comprehensively. This study addresses this gap by investigating the nuanced impacts of EDU on GHG emissions across quantiles and its interaction with FD to uncover whether education amplifies or mitigates emissions under varying conditions.

Third, although FD is widely recognized as a critical factor in environmental sustainability, its interaction with ENT and EDU in shaping GHG emissions remains underexplored. This study introduces interaction terms to examine how FD moderates the effects of ENT and EDU on emissions, providing insights into how financial systems can either enhance or offset the environmental benefits of these variables.

Lastly, the majority of existing studies rely on conventional econometric techniques that often fail to account for cross-sectional dependence and slope heterogeneity, which are prominent in panel datasets involving multiple nations. This study employs second-generation econometric methods, such as MMQR and Westerlund cointegration, to ensure robust and reliable findings. By focusing on the E−7 nations, which are pivotal in global emissions reduction efforts due to their economic size and rapid industrialization, the study fills a critical gap in understanding how policy interventions can balance economic growth and environmental sustainability in emerging economies.

3 Data and methods

3.1 Data description

The current study examines the long-term effects of FD, education, and environmental innovations on ENT and GHG in the E−7 countries. The study did this by using panel data from 1990 to 2019, as the Penn World Table, which is the source for the education variable, provides data only up to 2019, thereby determining the time frame of the analysis. GHG is the dependent variable, and ENT, FD, and EDU are the explanatory variables. Table 1 contains the data source, units, and symbol, while Figure 1 (scatter plot) and 2 (box plots) display the statistical summaries of the variables.

The scatter plot matrix above (Figure 1) illustrates the relationships between the variables used in the study, including GHG, ENP, ENT, FD, and EDU, alongside their respective Pearson correlation coefficients. Notable features of the data structure include the following:

(i) Strong Positive Correlation: A strong positive linear relationship is observed between ENT and GHG (Pearson's r = 0.75807), indicating that energy transition significantly impacts greenhouse gas emissions in the E7 countries.
(ii) Moderate Positive Correlation: ENP shows a moderate positive correlation with GHG (Pearson's r = 0.1692), reflecting the role of environmental patents in influencing emissions, albeit to a lesser extent.
(iii) Weak to Negligible Correlation: The relationships between FD and other variables, such as GHG and ENP, show weak correlations (Pearson's r = 0.33762 and 0.10293, respectively), suggesting a more complex, indirect influence on financial development.
(iv) Negative Correlation: A negative relationship is observed between EDU and GHG (Pearson's r = −0.4522), underscoring the role of education in potentially reducing emissions. Similarly, EDU negatively correlates with ENT, highlighting the impact of education on fostering sustainable energy practices.

The data distribution in the histograms along the diagonal provides insights into the variability and skewness of each variable. The elliptical patterns in scatter plots reflect the strength

TABLE 1 Data symbols and their sources.

Parameters	Symbol	Unit	Source
Financial development	FD	Financial development index	IMF
Energy transition	ENT	Ratio of renewable energy from primary energy	WDI
Education	EDU	Average years of schooling	Penn World Table
Greenhouse gas	GHG	Total greenhouse gas emissions equivalent to CO_2	OECD
Environmental technologies	ENP	Environmental Patents	OECD

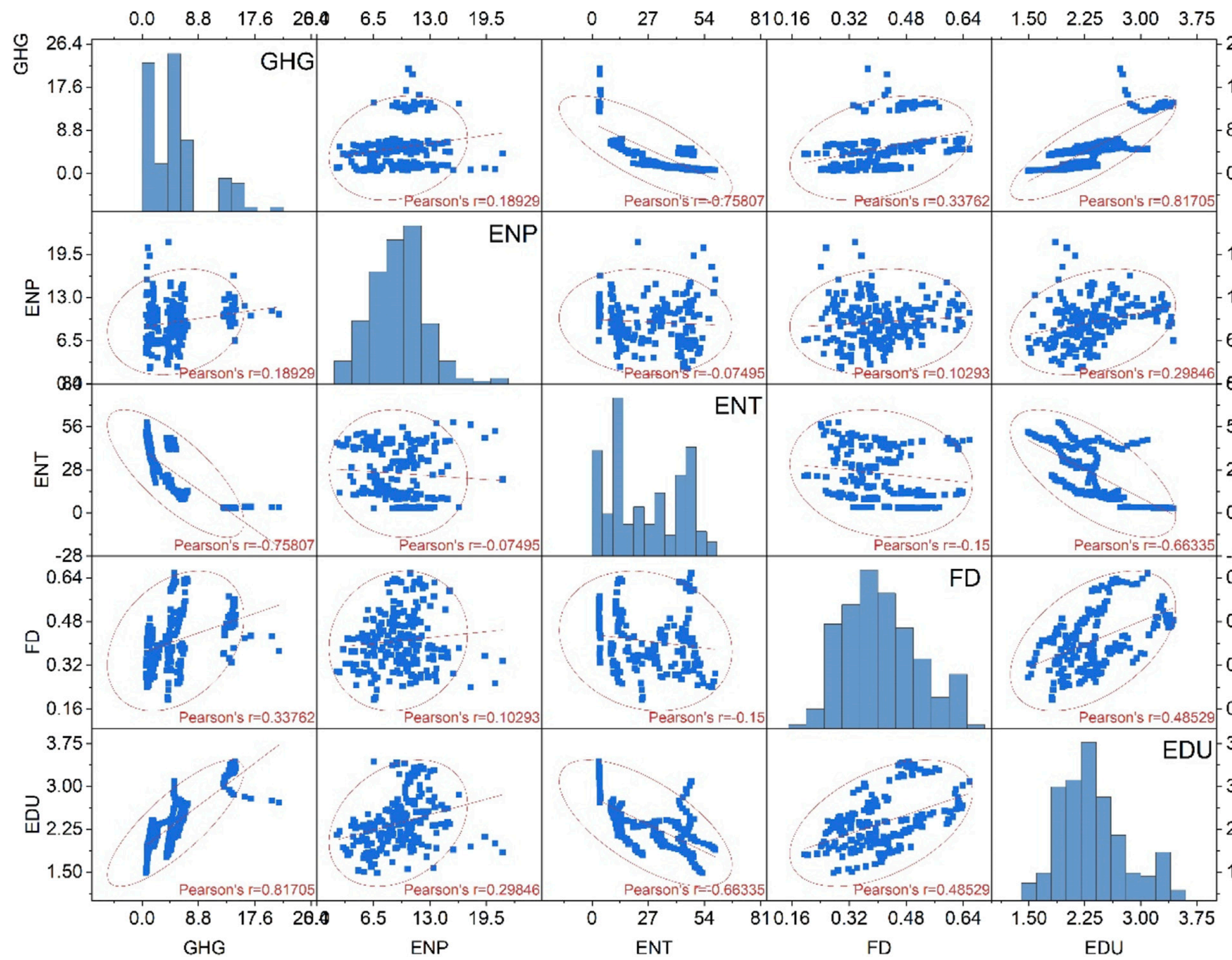

FIGURE 1
Scatter plot.

and direction of correlations. These visualizations offer a comprehensive overview of the interplay between variables and support the study's empirical analysis.

The box plots in Figure 2 provide a statistical summary of the range, distribution, and outliers for the variables used in this study—GHG, EDU, ENP, FD, and ENT. Below are the notable features of each variable's data structure:

(i) GHG: The box plot shows a wide range of values with a median close to the lower quartile, indicating a skewed distribution. The presence of a few extreme outliers suggests variability in GHG levels among the E7 countries.

(ii) EDU: The box plot for education shows a relatively narrow interquartile range (IQR), highlighting consistent education levels across countries. However, the distribution is slightly skewed upward, and a few outliers indicate disparities in higher education levels within some nations.

(iii) ENP: The box plot for ENP reveals a broad IQR with a concentration of values around the median, suggesting a

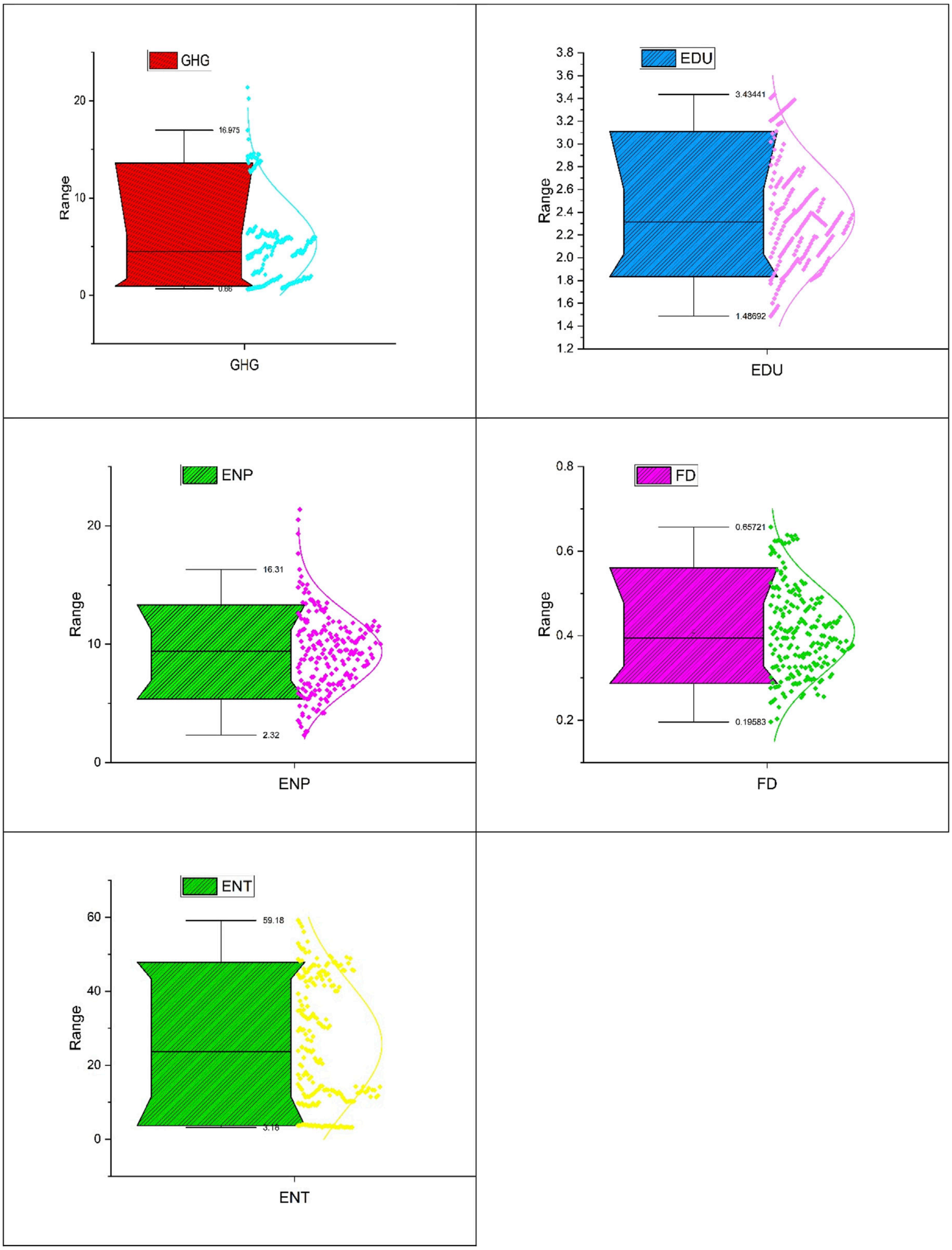

FIGURE 2
Box plots.

balanced distribution of environmental patent registrations. A few extreme outliers indicate countries with notably higher patent activity, reflecting disparities in innovation efforts.

(iv) FD: The financial development variable exhibits a compact range with a symmetric distribution, as indicated by the evenly spaced median and quartiles. Outliers are present, highlighting countries with significantly higher levels of financial development compared to others.

(v) ENT: The box plot for ENT shows a wide IQR with several outliers on the higher end, indicating that while most countries are transitioning energy usage at comparable rates, a few are progressing at much higher levels.

These box plots highlight key differences and trends within the E7 countries, providing insights into the variability and distribution of the variables under investigation. These visual representations serve as a foundation for deeper statistical and empirical analyses in the study.

The present study builds upon the research conducted by Qing et al. (2023), and Abbasi et al. (2022a), Abbasi et al. (2022b) to investigate the impact of different factors on GHG. The present study examines the enduring effects of ENP, financial development (FD), and education (EDU) on GHG. Equation 1 elucidates the underlying function of this study.

$$\text{LnGHG}_{it} = f\left(\text{LnENT}_{\text{it}}, \text{Ln ENP}_{\text{it}}, \text{LnFD}_{\text{it}}, \text{LnEDU}_{\text{it}}, \text{LnENT}*\text{FD}_{\text{it}}, \text{LnEDU}*\text{FD}_{\text{it}}\right) \quad (1)$$

The inclusion of interaction terms in Equation 1, specifically ENT × FD and EDU × FD, in the model serves to capture the combined or moderating effects of financial development (FD) on the relationship between ENT and EDU with greenhouse gas emissions. Interaction terms are particularly useful in examining how the influence of one independent variable on the dependent variable changes depending on the level of another independent variable.

In the above model, the ENT × FD term helps to analyze whether financial development amplifies or mitigates the impact of energy transition on greenhouse gas emissions. For example, financial development may provide the necessary resources and investments to accelerate energy transition processes, thereby enhancing its effect on reducing emissions. Alternatively, it could reveal scenarios where financial development inadvertently increases emissions by funding energy-intensive industries. Similarly, the EDU × FD interaction term explores how financial development interacts with education to influence greenhouse gas emissions. For instance, financial development may enable better educational outcomes or facilitate the implementation of environmentally conscious educational programs (Farooqi et al., 2024), potentially amplifying the role of education in promoting sustainability and reducing emissions.

By incorporating these interaction terms, the model can provide a nuanced understanding of how financial development influences the effectiveness of energy transition and education in reducing greenhouse gas emissions. It allows for the identification of synergistic or offsetting effects between variables, offering valuable insights for policymakers aiming to design integrated strategies for sustainable development in E7 countries.

3.2 Methodology

The interdependence among cross-sectional units has garnered significant attention in contemporary literature, resulting in numerous empirical investigations. The reason for this is that residuals exhibit a lack of independence within the actual context. Therefore, interdependence is inherent. The regional economies that are in the E–7 exhibit cross-border interconnections across various domains, including political, economic, social, environmental, and financial spheres. The correlation implies that any empirical inquiry conducted on these economies must consider the presence of cross-sectional dependence (CD). Equation 2 is proposed to investigate the CD in the data.

$$\text{CD}_{TM} = \left[\frac{TN(N-1)}{2}\right]^{\frac{1}{2}}\bar{\rho}_N \quad (2)$$

The correlation between the parameters is represented by P_{N} over the time interval T. Furthermore, an inquiry into the heterogeneity present in the slope coefficient has been carried out using the Pesaran and Yamagata (2008) test, which is a revised variant of Swamy's (1970) test. Equation 3 has been proposed in this context.

$$\tilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\tilde{S}-2k\right) \quad (3)$$

In the context being discussed, N is used to represent the cross-sectional units, while K is utilized to denote the explanatory variables. Upon examining the heterogeneity present in the slope coefficients, analysis has been carried out to determine the order of integration between the variables using both the cross-sectionally augmented IPS (CIPS) test and the cross-sectionally augmented Dickey-Fuller (CADF) test. Nonetheless, researchers must give considerable attention to the matter of erotic outcomes during regression estimation.

Hence, the present research has utilized the stationarity test, wherein the Co-Integration Augmented Dickey-Fuller (CADF) test has been elucidated in Equation 4 of the study.

$$\Delta Y_{i,t} = \gamma_i + \gamma_i Y_{i,t-1} + \gamma_i \bar{X}_{t-1} + \sum_{l=0}^{p}\gamma_{il}\Delta\bar{Y}_{t-l} + \sum_{l=1}^{p}\gamma_{il}\Delta Y_{i,t-l} + \varepsilon_{it} \quad (4)$$

The lagged parameter is denoted as Y_{t-1} and the initial difference of Y_{t-1} is represented by ΔY_{t-1}. The computation of CIPS statistics involves the determination of the mean of CADF, which is elucidated in the following Equation 5.

$$\widehat{\text{CIPS}} = \frac{1}{\text{N}}\sum_{\text{i}=1}^{\text{n}}\text{CADF}_{\text{i}} \quad (5)$$

Subsequently, an examination of the cointegrated relationship among the specified factors, namely, natural resources, digitalization, financial inclusion, government effectiveness, and human development, was carried out using the Westerlund (2005) cointegration test. After the confirmation of co-integration, this work moves forward to apply a novel nonlinear econometric method, namely, the Method of momentum quantile regression (MMQR) by (Machado and Santos Silva, 2019). Traditional linear econometric methods have only focused on modeling the mean of panel data, rather than the conditional distribution (Dogan et al., 2020). In contrast, MMQR panel estimation examines the relationship concerning variables across multiple quantiles. The technique by Koenker (2005) is generally used to approximate the linkages between several factors at different quantiles.

Quantile regression is a statistical method that is resistant to the influence of outliers and generates effective estimates for data sets with heavy tails. According to Binder and Coad (2011), the method maintains consistency even when multicollinearity is present. However, it should be noted that the quantile regression model exhibits a limitation in its ability to ensure noncrossing outcomes for a multitude of percentiles, which may lead to an inaccurate representation of the response distribution.

Considering the context, it is recommended to utilize MMQR owing to a multitude of factors. The model yields consistent results even in the presence of unobserved endogeneity and heterogeneity across the cross-sections. The MMQR methodology allows for the conditional and heterogeneous influence of ecological footprint determinants to impact the distribution's quantiles. This approach proves advantageous in cases where explanatory variables exhibit high correlation and endogenous behavior.

It works for high-kurtosis nonlinear data sets. It captures data dynamics endogenously, making it better than other nonlinear modeling methods (Shin et al., 2014). Since parameters depend on response variable location, MMQR allows for asymmetric variable location. Partial-parametric modeling structures like MMQR are ideal for dealing with asymmetry, heterogeneity, and endogeneity producing estimates across numerous quantiles (Wang and Razzaq, 2022). The amended location-scale definition for conditional quantiles Q(X) is in Equation 6.

$$y_{it=}\beta_i + X_{it}\alpha + (\delta_i + U_{it}\gamma)c_{it} \tag{6}$$

The probability (p) can be expressed as P (δi + Uitγ > 0) = 1, where (β, α, δ, γ) are the assessed factors (βi, δi), i = 1, . . . N, that confirm the fixed effects of individual i. Here, U represents a chosen j-vector element of X that accounts for difference transformation in the equation, denoted as Ul = Ul (X), l = 1, ...j. Furthermore, it can be observed that Xit denotes an equivalent distribution for a given individual at a distinct point in time (T). Assuming identical distribution at an individual level (i) for time (T), Zit is impertinent to Machado and Santos Silva, (2019) instants conditions. The model can be expressed in its quantile in the following manner in Equation 7.

$$Q\tau\left(\frac{\tau}{X}\right) = (\beta_i + \delta i_p(\tau)) + X_{it}\alpha + U_{ityp} \tag{7}$$

The variables FD, EDU, ENT, and ENP, are represented as Xit, while Qτ (τ/X) denotes the dependent factor Y_{it}, which is the GHG, conditioned on fundamental quantiles and placed as the independent factors. The notation βi (τ) = βi + δip (τ) is used to denote the quantile τi for an individual. The parameter attains a fixed state and exhibits significant heterogeneous effects, thereby enabling the quantile model τth to manifest through q (τ) derived from the linearity problem in Equation 8.

$$\min_q \sum_i \sum_t \pi_\tau (W_{it} - (\vartheta_{it} + Z_{it}\theta)q) \tag{8}$$

The check function, denoted by the equation above, is in Equation 9.

$$\pi_\tau(A) = (\tau - 1)AI\{A \le 0\} + TAI\{A > 0\} \tag{9}$$

TABLE 2 Descriptive statistics.

	GHG	EDU	ENP	ENT	FD
Mean	5.229455	2.353403	9.337321	25.97057	0.408082
Median	4.488000	2.311838	9.395000	23.92000	0.394878
Maximum	21.37400	3.434408	21.37000	59.18000	0.657214
Minimum	0.610000	1.486921	2.320000	3.180000	0.195825
Std. Dev	4.285231	0.449853	3.211827	16.84628	0.104497
Skewness	1.387064	0.599218	0.497425	0.184009	0.434630
Kurtosis	4.458222	2.854157	3.990714	1.570874	2.568678
Jarque-Bera	85.94423	12.75329	17.24835	19.05610	8.239446
Probability	0.000000	0.001701	0.000180	0.000073	0.016249

4 Results and discussion

This section provides the analysis and discussion of the results. For this purpose, this work provides results of CD, unit root tests, slope tests, co-integration tests, and MMQR analysis.

The descriptive statistics presented in Table 2 provide insights into the central tendencies, variability, and distribution of the variables used in this study: GHG, EDU, ENP, ENT, and FD. The mean value of GHG emissions is 5.23, reflecting the average level of greenhouse gas emissions across the E−7 economies during the study period. EDU has a mean value of 2.35, indicating a moderate level of educational attainment among the countries, while ENP has a mean value of 9.33, suggesting a relatively higher intensity of environmental patent activity. ENT, representing energy transition, exhibits the highest mean value at 25.97, highlighting its significance and variability among the E−7 nations. In contrast, FD, with a mean value of 0.40, represents the lowest average level among the variables, reflecting the relatively limited financial development in these economies.

The maximum and minimum values further demonstrate the wide range of variability within the dataset. ENT has the highest maximum value at 59.18, emphasizing significant disparities in energy transition progress across the E−7 countries. On the other hand, FD shows the smallest minimum value at 0.195, indicating substantial variation in financial development levels. The standard deviation values also support this observation, with ENT having the largest standard deviation (16.85), reflecting high variability, and FD the smallest (0.10), suggesting relatively stable levels across the panel.

The skewness and kurtosis statistics reveal additional details about the data distribution. GHG is positively skewed (1.38), indicating that higher values of emissions are more prevalent (see Figure 3), while EDU, ENP, ENT, and FD are moderately skewed. The kurtosis of GHG (4.46) suggests a leptokurtic distribution with fatter tails, whereas ENT (1.57) shows a platykurtic distribution, indicating thinner tails and less extreme data points.

Finally, the Jarque-Bera test results indicate that the variables GHG, EDU, ENP, and ENT deviate significantly from normality (p-values <0.05), while FD shows a relatively lower deviation. These statistics highlight the heterogeneity and unique characteristics of the variables across the E−7 countries, which is essential for understanding the underlying dynamics in the analysis.

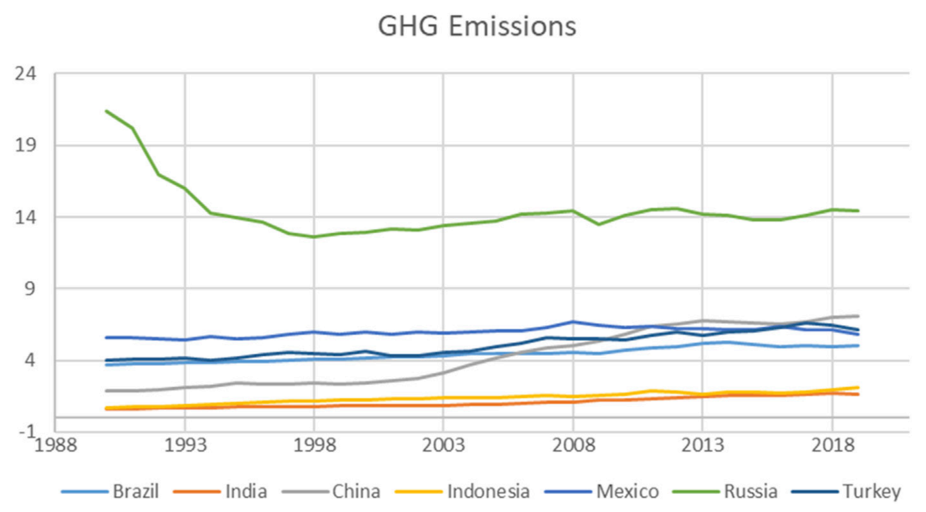

FIGURE 3
Trend of GHG emissions in E7 nations during 1990–2019.

TABLE 3 CD test.

Variable	Test statistics
GHG	13.35[a]
EDU	23.84[a]
ENP	1.53
ENT	17.55[a]
FD	17.65[a]

[a]Note: explains the level of significance at 1%.

TABLE 4 Slope heterogeneity test.

	Value	P-Value
Delta	−0.910	0.336
Adj	−1.929[b]	0.054

[b]Note: explain the level of significance at 5%.

The cross-sectional dependence (CD) test presented in Table 3 evaluates whether the variables in the panel data are interdependent across the E−7 countries. Cross-sectional dependence is a crucial diagnostic step in panel data analysis, as ignoring CD can lead to biased and inefficient estimates. The test statistics for each variable provide insights into the presence and extent of cross-sectional dependence.

The results of CD indicate that GHG, EDU, ENT, and FD exhibit significant cross-sectional dependence at the 1% significance level. For example, the CD test statistic for GHG is 13.35, confirming strong interdependence in greenhouse gas emissions among the E−7 economies. This suggests that emissions in one country are not isolated but may be influenced by economic, environmental, or policy factors in other E−7 nations. Similarly, the high CD statistic for education (23.84) indicates that education systems and developments are also interconnected across these countries, potentially reflecting similarities in policy frameworks or shared regional challenges.

ENT and FD show test statistics of 17.55 and 17.65, respectively, further supporting the presence of cross-sectional dependence. This interdependence may arise due to shared global or regional initiatives, such as commitments to the Paris Agreement, or the integration of financial markets across these emerging economies. The interconnectedness of ENT highlights the potential spillover effects of energy transition policies, while FD's CD indicates the influence of financial integration and global capital flows among the E−7 nations.

In contrast, environmental patents exhibit a relatively low CD test statistic of 1.53, which does not reach statistical significance. This finding suggests that ENP activities may be less influenced by cross-country dynamics and more driven by domestic factors, such as national innovation policies or industry-specific developments.

Overall, these results emphasize the need to account for cross-sectional dependence in the panel data analysis. Failure to do so could lead to inaccurate inferences, as traditional panel data methods assume independence across cross-sections. By addressing CD, the study ensures robust and reliable estimations of the relationships between the variables, providing meaningful insights for policymakers and stakeholders in the E−7 economies.

The slope heterogeneity test presented in Table 4 evaluates whether the slope coefficients across the panel data are homogeneous or vary significantly across cross-sectional units (countries). Testing for slope heterogeneity is critical because panel data models with heterogeneous slopes can produce biased estimates if treated as homogeneous. The findings are reported in terms of the delta statistic and its adjusted value.

The delta statistic is −0.910 with a p-value of 0.336, indicating that the null hypothesis of slope homogeneity cannot be rejected at conventional significance levels. Similarly, the adjusted delta statistic of −1.929 with a p-value of 0.054 shows marginal evidence of slope heterogeneity but remains statistically insignificant at the 5% level. These results suggest that the slopes are homogeneous across the

TABLE 5 Unit root test.

Variable	CADF		CIPS	
	At level	1st difference	At level	1st difference
$lnGHG_t$	−2.344	−2.936[b]	−2.020	−4.615[a]
$lnEDU_t$	−2.016	−2.786[b]	−0.949	−2.786[b]
$lnENP_t$	−4.677	−6.167[a]	−4.677	−6.167[a]
$lnENT_t$	−2.042	−4.674[a]	−2.042	−4.674[a]
$lnFD_t$	−2.545	−5.380[a]	−2.545	−5.380[a]

Note:[a]and[b]. explain the level of significance at 1% and 5%, respectively.

E−7 countries, meaning that the relationships between the variables, such as GHG, education, energy transition, financial development, and environmental patents, are consistent across the cross-sectional units.

The homogeneity of slopes ensures that a single relationship applies uniformly to all the E−7 countries in the analysis, simplifying the interpretation and facilitating the use of panel data techniques that assume homogeneity. This finding justifies the application of co-integration and unit root tests that account for cross-sectional dependence (CD). Addressing both CD and slope homogeneity ensures that the analysis captures the interconnectedness of the E−7 economies while maintaining the validity of panel estimators.

To confirm the stationarity properties of the variables in the presence of CD, the study employs second-generation unit root tests, specifically the CIPS (Cross-sectionally Augmented IPS) and CADF (Cross-sectionally Augmented Dickey-Fuller) tests. These tests are superior to first-generation unit root tests because they account for cross-sectional dependence, thereby providing more reliable results. The combination of homogeneous slopes and advanced unit root testing methods strengthens the robustness of the analysis, ensuring that the relationships between the variables are properly captured and interpreted. This comprehensive approach enhances the reliability and validity of the study's findings, offering valuable insights into the dynamics of GHG emissions, education, financial development, and energy transition in the E−7 economies.

The unit root test results in Table 5, based on CADF and CIPS tests, indicate the stationarity properties of the variables GHG, EDU, ENP, ENT, and FD. At the level, most variables fail to achieve stationarity, as evidenced by test statistics that do not meet the critical values for significance. However, after first differencing, all variables become stationary, as shown by significant CADF and CIPS statistics at the 1% or 5% significance levels.

For example, GHG becomes stationary at the first difference with a CADF statistic of −2.936 (5% level) and a CIPS statistic of −4.615 (1% level). Similarly, education (EDU), which is non-stationary at the level, becomes stationary after differencing, with a CADF statistic of −2.786 (5% level). Environmental patents, energy transition, and financial development (FD) are also integrated at the first difference, with strong statistical significance.

These results confirm that all variables are integrated of order one (I (1)), justifying the application of cointegration techniques to examine long-term relationships among the variables. By accounting for cross-sectional dependence and ensuring stationarity at the first difference, the study ensures the robustness and validity of subsequent econometric analyses.

TABLE 6 Westerlund test.

Stat	Value	Z value	P-Value
G_t	−1.886	0.238	0.594
G_a	−5.454	1.646	0.950
P_t	−10.283[a]	−4.741	0.000
P_a	−12.956	−2.476	1.007

[a]Note: explains the level of significance at 1%.

The Westerlund cointegration test results presented in Table 6 provide mixed evidence regarding the existence of a long-term relationship among the variables ENT, GHG, ENP, FD, and EDU across the models examined in this study. The test assesses whether the panel data exhibit cointegration by comparing four statistics: G_t, G_a, P_t, and P_a, with the null hypothesis being no cointegration.

The Pt statistic shows a value of −10.283 with a Z-value of −4.741 and a p-value of 0.000, indicating a statistically significant rejection of the null hypothesis at the 1% level. This provides strong evidence of cointegration in the panel, suggesting that the variables share a long-term equilibrium relationship. Similarly, the Pa statistic, while less conclusive, points toward cointegration with a Z-value of −2.476. However, its p-value of 1.007 does not meet conventional significance thresholds, indicating weaker support for rejecting the null hypothesis in this case.

Conversely, the G_t and G_a statistics fail to reject the null hypothesis, with p-values of 0.594 and 0.950, respectively. These results suggest no evidence of cointegration when examining group-specific dimensions of the panel.

Despite the mixed results, the strong significance of the P_t statistic underscores the robustness of the evidence for a long-term relationship at the panel level, aligning with the study's hypothesis that ENT, ENP, FD, and EDU collectively influence GHG over time. The next step involves estimating the long-run coefficient values to quantify these relationships. For this purpose, the MMQR approach is applied, enabling a more detailed exploration of how these variables interact across the GHG distribution and providing further validation for the findings.

The MMQR results for the nine quantiles offer a comprehensive view of how the independent variables and interaction terms impact GHG emissions across different parts of the distribution. These results highlight the heterogeneity in the relationships and provide

TABLE 7 MMQR results.

Variable	Location	Scale	Quantiles								
			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
EDU	3.856	−3.062	7.695[b]	6.780[a]	6.327	5.781[b]	4.125	2.355	1.192	0.126	−0.904[a]
ENP	−0.166	−0.067[a]	−0.081[a]	−0.101[b]	−0.111	−0.123	−0.160[b]	−0.198	−0.224[a]	−0.248[a]	−0.270[b]
ENT	−1.001[a]	1.002[a]	−2.257[a]	−1.958[a]	−1.810[a]	−1.631[a]	−1.089[a]	−0.510[a]	−0.130[a]	0.219[a]	0.556[a]
FD	−0.816	−1.055	0.507	0.192	0.036[b]	−0.152[b]	−0.723	−1.333[a]	−1.734	−2.101	−2.456[b]
EDU*FD	−0.872	0.658	−1.697	−1.501	−1.403	−1.286	−0.930	−0.549	−0.299	−0.070	0.151
ENT*FD	0.424	−1.126[b]	1.836[b]	1.499[a]	1.333[a]	1.132[b]	0.523[b]	−0.128[b]	−0.556[b]	−0.948[b]	−1.327[a]

Note:[a]and[b] explain the level of significance at 1% and 5%, respectively.

insights into the varying influences of education, environmental patents, energy transition, financial development, and their interactions (EDU*FD and ENT*FD) in the E7 economies.

According to the results presented in Table 7, the variables ENT, EDU, and ENP were found to be statistically significant across most quantiles, while their impact varied depending on the quantile under consideration. These variables play a crucial role in influencing GHG emissions and improving environmental quality in the E−7 economies. An increase of 1% in ENT exhibits a consistent reduction in GHG emissions across the majority of quantiles, particularly quantiles 0.10 to 0.70, with its effect being most pronounced at lower quantiles (e.g., −2.257 at 0.10) and gradually weakening at higher quantiles (e.g., −0.130 at 0.70). This underscores the importance of ENT in promoting environmental sustainability by transitioning to cleaner energy sources and low-carbon technologies, as corroborated by Ullah et al. (2022), Qing et al. (2023), and Wen et al. (2022). The adoption of renewable energy (RE) sources such as wind and solar energy, along with energy-efficient technologies, significantly mitigates GHG emissions (Murshed et al., 2022). Furthermore, low-carbon transportation solutions, including electric vehicles and public transport systems, have been found to play a pivotal role in reducing emissions from the transportation sector, a major source of GHG (Qing et al., 2023).

Environmental patents consistently exhibit a negative relationship with GHG emissions across all quantiles (from −0.101 at 0.20 to −0.270 at 0.90), with their impact becoming stronger at higher quantiles. For instance, at the 0.90 quantile, a 1% increase in ENP reduces GHG emissions by 0.27%. This finding suggests that ENP is particularly effective in reducing emissions in high-emitting economies, emphasizing its role in fostering sustainable practices and optimizing resource use. Studies by Appiah-Otoo et al. (2022) and Tzeremes et al. (2023) corroborate the positive effects of technological innovation, especially smart grid systems and efficient energy technologies, in mitigating emissions. The integration of ENP promotes the efficient use of RE sources, reducing dependency on fossil fuels and fostering green energy adoption (Wen et al., 2022; Jahanger et al., 2022). It has gained prominence as a viable approach to mitigating GHG emissions through the promotion of sustainable practices and the optimization of resource utilization. The employment of smart grid approaches has the potential to enhance the efficient electricity supply and mitigate energy wastage, thereby resulting in a substantial decrease in GHG (Onifade and Alola, 2022). This highlights the importance of leveraging innovation to address the environmental challenges posed by rapid industrial and economic structural transformations in E7 nations.

Financial development presents a more complex relationship with GHG. In the MMQR findings, FD shows significant variability in its effect across quantiles. While FD has a limited or marginally positive effect on GHG at lower quantiles (e.g., 0.507 at 0.10), it becomes increasingly negative and significant at higher quantiles (e.g., −2.456 at 0.90). This suggests that financial development in economies with higher emissions is more effective in facilitating investments in green projects and supporting sustainable practices. For instance, a 1% increase in FD at the 0.90 quantile leads to a 2.46% reduction in GHG emissions, demonstrating the transformative role of sustainable finance in high-emission contexts. However, as Zhang (2011), Acharya (2003), and Sharma et al. (2019) noted, FD can also increase emissions through greater consumption of carbon-intensive goods and heightened energy demand driven by investment activities. Therefore, balancing the positive and negative effects of FD is critical. Sustainable finance frameworks can direct FD towards eco-friendly projects and RE technologies, reducing its adverse environmental impacts.

Education shows a dynamic effect on GHG, with a positive influence at lower quantiles that gradually becomes negative at higher quantiles. For instance, EDU has a statistically significant positive effect at quantiles 0.10 (7.695) and 0.20 (6.780), reflecting its role in industrial expansion and urbanization, which can increase emissions, as noted by Nathaniel, Barua, and Ahmed (2021). Conversely, at the higher quantiles, such as 0.90 (−0.904), a 1% increase in EDU reduces GHG by approximately 0.90%. This pattern reflects the transformative potential of education in fostering energy-efficient practices, RE investments, and sustainable development (Sezgin et al., 2021). These findings underscore the dual role of education in E7 economies—both as a driver of emissions in the early stages of development and as a mitigating factor as economies mature.

The interaction terms, ENT × FD and EDU × FD, further amplify the impact of energy transition and education on GHG emissions, particularly in high-emission contexts. ENT × FD shows a positive effect at lower quantiles (e.g., 1.836 at 0.10) but turns negative at higher quantiles (e.g., −1.327 at 0.90). This indicates that financial development initially supports energy transition efforts but

TABLE 8 Fixed-effect (Robustness test).

GHG	Value	P-Value
EDU	−0.464[b]	0.037
ENP	−0.014	0.538
ENT	−0.523[a]	0.001
FD	−0.504[b]	0.014
EDU*FD	0.377[b]	0.029
ENT*FD	−0.508[b]	0.016
R-squared	0.723	-

Note: [a]and[b] explain the level of significance at 1% and 5%, respectively.

becomes more effective at mitigating emissions as GHG levels increase. Similarly, EDU × FD exhibits a diminishing negative effect across quantiles, with its impact being strongest at 0.10 (−1.697) and weakest at 0.90 (0.151). These findings align with Sezgin et al. (2021), who highlighted the importance of directing financial resources toward sustainable projects to maximize the positive environmental effects of financial development and education. However, overemphasis on short-term financial returns could undermine long-term sustainability goals, particularly in economies undergoing structural transformations.

The updated MMQR findings provide a nuanced understanding of the environmental impacts of economic structural transformations in the E−7 economies. Rapid industrialization and urbanization, while essential for economic growth, have heightened emissions challenges. The results emphasize the need for targeted policies that integrate education, innovation, and financial development with energy transition strategies to address the environmental consequences of such transformations (Hariguna, 2023). By aligning financial and technological efforts with sustainability objectives, the E−7 nations can mitigate the adverse impacts of their structural economic transitions and contribute meaningfully to global efforts to combat climate change. These insights are critical for policymakers aiming to achieve sustainable development goals in the context of emerging economies.

The fixed-effects results in Table 8 provide a robustness check to validate the findings of the MMQR analysis, offering insights into the relationships between GHG emissions and the explanatory variables (EDU, ENP, ENT, FD, EDU × FD, and ENT × FD). The fixed-effects model accounts for unobservable heterogeneity across the E7 countries, ensuring that the relationships are not confounded by country-specific effects.

The results reveal that EDU has a negative and statistically significant effect on GHG emissions at the 5% significance level, with a coefficient of −0.464. This finding aligns with the MMQR results at higher quantiles, where EDU was observed to reduce GHG emissions, especially in countries with higher emissions. It reinforces the argument that education fosters sustainable practices, energy-efficient behavior, and awareness of environmental issues, thereby contributing to emissions reduction. However, the fixed-effects coefficient is smaller in magnitude compared to the MMQR results, indicating a less pronounced but consistent impact of EDU on emissions in the fixed-effects framework.

ENP, on the other hand, show a negative but statistically insignificant relationship with GHG emissions (coefficient: 0.014, p-value: 0.538). This result differs from the MMQR findings, where ENP consistently showed a significant negative effect across most quantiles, particularly at higher quantiles. The lack of significance in the fixed-effects model may suggest that the impact of ENP is more nuanced and context-dependent, varying across different parts of the GHG distribution, which the MMQR captures more effectively.

Energy transition (ENT) exhibits a significant negative effect on GHG emissions, with a coefficient of −0.523 (1% significance level). This result is consistent with the MMQR findings, confirming that ENT is a crucial driver of emissions reduction in the E7 economies. The robustness of this result across both models highlights the importance of scaling up energy transition efforts to achieve environmental sustainability.

Financial development (FD) also demonstrates a significant negative impact on GHG emissions, with a coefficient of −0.504 (5% significance level). This finding validates the MMQR results at higher quantiles, where FD was shown to reduce emissions in high-emission contexts. It underscores the role of financial development in mobilizing resources for green investments and fostering sustainable economic growth.

The interaction terms provide additional insights. The interaction of education and financial development (EDU × FD) has a positive and significant effect on GHG emissions, with a coefficient of 0.377 (5% significance level). This suggests that while education and financial development individually reduce emissions, their combined effect might lead to increased consumption or energy use, potentially offsetting their standalone benefits. This finding aligns with the MMQR results at lower quantiles, where similar dynamics were observed.

The interaction of energy transition and financial development (ENT × FD) shows a negative and significant effect on GHG emissions, with a coefficient of −0.508 (5% significance level). This supports the MMQR results at higher quantiles, highlighting that financial development enhances the effectiveness of energy transition efforts in reducing emissions, particularly in high-emission economies. The R-squared value of 0.723 indicates that the fixed-effects model explains approximately 72.3% of the variance in GHG emissions, suggesting a good fit for the data.

In summary, the fixed-effects results largely validate the findings of the MMQR analysis. Both models highlight the critical roles of ENT, FD, and EDU in reducing GHG emissions, while the interaction terms further emphasize the importance of integrating financial development with education and energy transition strategies. The differences in the significance and magnitude of certain variables, such as ENP, underscore the value of MMQR in capturing heterogeneity across the GHG distribution, offering complementary insights to the fixed-effects model. Together, these results provide robust evidence for policymakers to design targeted strategies for achieving environmental sustainability in the E7 economies.

5 Conclusion and recommendations

This study was undertaken to examine the enduring impact of environmental innovations (ENP), financial development (FD), energy transition (ENT), and education (EDU) on GHG emissions in the E−7 nations. Using second-generation econometric techniques, such as Westerlund cointegration and MMQR, the analysis spanned the period from 1990 to 2019. The findings highlight the significant contributions of ENT and ENP to long-term GHG reduction, while EDU exhibited a consistent positive influence on GHG across all quantiles, reflecting its role in emissions growth during economic transitions.

The MMQR results provide nuanced insights across lower and higher quantiles. ENT and ENP both exhibit negative impacts on GHG emissions across all quantiles, with ENT's influence being more pronounced at lower quantiles, where initial emissions levels are lower, and ENP's effect becoming stronger at higher quantiles, demonstrating its critical role in mitigating emissions in high-emitting economies. Conversely, EDU consistently shows a positive relationship with GHG emissions across all quantiles, with its impact diminishing at higher quantiles. This reflects how increasing education levels in transitional economies drive industrial expansion, urbanization, and higher energy consumption, which subsequently raise emissions. FD exhibits a mixed effect: while its impact on GHG is relatively minor at lower quantiles, it turns negative and significant at higher quantiles, highlighting its capacity to support green investments and reduce emissions in high-emission contexts.

The robustness check validates key MMQR findings, particularly the negative effects of ENT and FD on GHG emissions. It also highlights the dual role of EDU, which can drive emissions in some scenarios (as reflected in the MMQR) while reducing them under certain economic and institutional contexts (as shown in the fixed-effects model). ENP's insignificance in the robustness test may suggest its country-specific relevance, a nuance effectively captured in the quantile-specific MMQR analysis.

In conclusion, this study underscores the need for targeted policy interventions that leverage ENT and ENP to reduce GHG emissions and strategically direct FD toward sustainable investments. The dual nature of EDU necessitates careful policymaking to harness its potential for emissions reduction while mitigating its contributions to emissions growth in transitional economies. These findings offer critical insights for E−7 nations striving to balance economic growth with environmental sustainability effectively.

5.1 Policy suggestions

This study presents a discussion of the empirical evidence supporting policy recommendations for the E−7 countries in their pursuit of sustainable development goals (SDGs) related to energy and the environment, particularly SDG7 and SDG-13. One of the primary policy options is to prioritize the advancement of research and development in cutting-edge technologies, while also providing incentives to encourage their widespread implementation, adoption, and dissemination. To bolster these policy objectives, governmental bodies can provide economic inducements, such as tax credits and subsidies, to enterprises that allocate resources towards the development and implementation of environmentally sustainable technologies. Policymakers possess the ability to facilitate the establishment of public-private collaborations that promote assistance among academia, industry, and authority, to devise and execute green energy solutions. These policy measures have the potential to expedite the widespread implementation of environmentally friendly technologies, facilitate the transition towards sustainable energy sources, and mitigate GHG.

In a similar vein, the provision of incentives for green finance represents an additional avenue through which sustainable development initiatives can be bolstered. This objective can be accomplished through the implementation of policies that facilitate the issuance of green bonds or other financial instruments. Finally, it is crucial to emphasize that allocating resources towards education has the potential to cultivate a workforce that is well-informed and proficient, thereby enabling the development and implementation of environmentally friendly technologies. Education can also facilitate the cultivation of knowledge and understanding, leading to increased awareness and subsequent modification of behavior towards more sustainable practices. This, in turn, contributes to the development of a society that is more sustainable and environmentally conscious.

5.2 Study limitations and future directions

While this study provides valuable insights into the impact of environmental innovations, financial development, energy transition, and education on greenhouse gas emissions in E−7 nations, several limitations merit attention. First, the reliance on panel data for the 1990–2019 period may restrict the generalizability of the findings, as more recent developments in green technologies and policy frameworks are not captured. This limitation is particularly relevant given the rapid advancements in renewable energy technologies and financial instruments for sustainable development in recent years. Future research could benefit from extending the dataset to include more recent years, capturing the dynamic evolution of these variables and their interactions in response to global sustainability efforts.

Second, although the study employs advanced econometric techniques such as MMQR and fixed-effects models, it does not fully explore potential non-linear dynamics or threshold effects that might exist between the explanatory variables and GHG emissions. For instance, the relationship between financial development and environmental sustainability may exhibit non-linear patterns, where the impact varies significantly depending on the stage of economic development or the maturity of financial institutions. Future research could incorporate non-linear models or explore threshold-based approaches to provide a more nuanced understanding of these relationships.

Third, the findings related to education's dual role in influencing GHG emissions suggest the need for a deeper investigation into the contextual factors driving this duality. While education promotes environmental awareness and sustainable practices, it may simultaneously encourage energy-intensive lifestyles and consumption patterns in transitional economies. Future studies could focus on disaggregated educational indicators, such as levels of education (primary, secondary, tertiary) or specific environmental education initiatives, to better understand their differential impacts on emissions.

Additionally, this study does not account for country-specific institutional and policy variations, which can significantly mediate the relationships under investigation. E–7 countries exhibit diverse economic structures, regulatory environments, and governance capacities, which may influence the effectiveness of energy transitions, environmental innovations, and financial development in reducing emissions. Future research could adopt a more granular approach, integrating country-specific factors such as institutional quality, regulatory frameworks, and cultural attitudes toward sustainability.

Lastly, the study primarily focuses on direct impacts and moderating effects, leaving unexplored potential spillover effects across nations. In an increasingly interconnected global economy, policies or advancements in one E–7 country may influence environmental outcomes in others through trade, investment, and technology transfer. Future research could utilize spatial econometric models to examine these spillover effects, offering a more comprehensive view of the interdependencies among E–7 nations in addressing climate change. By addressing these limitations, future studies could build on the findings presented here, contributing to a deeper understanding of the pathways toward sustainable development in emerging economies.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://databank.worldbank.org/source/worldwide-governance-indicators.

Author contributions

BZ: Formal Analysis, Methodology, Resources, Writing–original draft, Writing–review and editing. YW: Funding acquisition, Methodology, Supervision, Validation, Writing–original draft, Writing–review and editing. ML: Conceptualization, Funding acquisition, Methodology, Project administration, Software, Validation, Writing–original draft, Writing–review and editing. UM: Conceptualization, Data curation, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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