Energy Conversion and Management: X 30 (2026) 101793

Contents lists available at ScienceDirect

Energy Conversion and Management: X

journal homepage: www.sciencedirect.com/journal/energy-conversion-and-management-x

Renewable energy and CO_2 emissions in middle-income economies: The roles of FDI, innovation, and industrialization under the EKC

Md Zahidul Islam [a,1], Md. Shamim Hossain [b,c,2], Mohammad Bin Amin [d,e,i,3,*], Judit Oláh [f,g,h,4]

[a] *Department of Management, Jatiya Kabi Kazi Nazrul Islam University, Mymensingh, Bangladesh*
[b] *School of Business, Faculty of Business, Design and Arts, Swinburne University of Technology, Sarawak Campus, Malaysia*
[c] *IUBAT School of Business, IUBAT - International University of Business Agriculture and Technology, Dhaka, Bangladesh*
[d] *Doctoral School of Management and Business, Faculty of Economics and Business, University of Debrecen, Böszörményi street 138, Debrecen 4032, Hungary*
[e] *Department of Business Administration, Faculty of Business Studies, Bangladesh Army University of Science and Technology, Saidpur 5310, Nilphamari, Bangladesh*
[f] *Faculty of Economics and Business, University of Debrecen, Böszörményi út 138, Debrecen 4032, Hungary*
[g] *Doctoral School of Management and Business Administration, John von Neumann University, 6000 Kecskemét, Hungary*
[h] *Department of Trade and Finance, Faculty of Economics and Management, Czech University of Life Sciences Prague, Czech Republic*
[i] *Department of Business Studies, State University of Bangladesh, 696 Kendua, Kanchan, Rupganj, Narayanganj, 1461, Dhaka, Bangladesh*

ARTICLE INFO

Keywords:
CO_2 emissions
Renewable energy
EKC hypothesis
Middle-income countries

ABSTRACT

The 2023 global CO_2 emissions are documented to exceed 36.8 billion tons, emphasizing the need for a balance between environmental sustainability and economic growth. Determining effective climate policies and strategies is crucial to addressing this challenge of reducing emissions while encouraging growth for sustainable development. Therefore, this study explores the relationship between renewable energy and CO_2 emissions within "the Environmental Kuznets Curve (EKC) framework" in middle-income countries (MICs), considering the roles of foreign direct investment (FDI), innovation, and industrialization. The study employs advanced econometric methods, including "the Common Correlated Effects Mean Group (CCEMG), the Dynamic Common Correlated Effects (DCCE) methods, and the Dumitrescu-Hurlin (D-H) causality test" to analyze panel data from 25 MICs. The overall results show an inverse U-shaped relationship between GDP per capita and CO_2 emissions, supporting the EKC hypothesis. The causality analysis discloses that most variables exhibit bidirectional relationships with CO_2 emissions, indicating mutual influence between these factors and environmental outcomes. The study reveals that while renewable energy significantly lowers CO_2 emissions in most MICs, various economic factors contribute to an overall increase in emissions in these nations. In fact, the economic growth of some countries is still related to higher emissions. Policies should focus on accelerating renewable energy use and promoting low-carbon technologies, while confirming that foreign investment, innovation, and industrial growth align with environmental sustainability. This approach aims to establish a robust growth-emissions pathway in MICs.

1. Introduction

The escalating pattern of carbon dioxide emissions from fossil fuel combustion reached a new peak of 36.8 billion metric tons in 2023. The total emissions, including deforestation and wildfires, amounted to around 40.9 billion metric tons [1]. However, middle-income countries

---

* Corresponding author at: Doctoral School of Management and Business, Faculty of Economics and Business, University of Debrecen, Böszörményi street 138, Debrecen 4032, Hungary.

E-mail addresses: zahidmgtdu@gmail.com, zahidmgt@jkkniu.edu.bd (M.Z. Islam), mhossain.bba@iubat.edu (Md.S. Hossain), binamindu@gmail.com, binaminbd@mailbox.unideb.hu (M.B. Amin), olah.judit@econ.unideb.hu (J. Oláh).

[1] ORCID: 0000-0003-3231-7953.
[2] ORCID: 0000-0002-8267-6471.
[3] ORCID: 0000-0002-9184-4828.
[4] ORCID: 0000-0003-2247-1711.

https://doi.org/10.1016/j.ecmx.2026.101793
Received 22 January 2026; Received in revised form 11 March 2026; Accepted 21 March 2026

are at a critical juncture, where rapid industrialization, innovation, urbanization, and economic expansion increase emissions. According to [2], MICs account for nearly 70% of global CO_2 emissions. MICs are in a critical phase of their economic growth. As their GDP and industries grow, they impose greater pressure on the environment. To reduce emissions while keeping the economy growing, it is significant to include renewable energy and low-carbon technologies in economic initiatives. This unique condition is well-suited for exploring the dynamics of the EKC theory. Therefore, extensive research on effective mitigation strategies is necessary, especially in MICs where overseas funding, innovation, and industrialization significantly impact environmental pollution.

The EKC theory has provided a conceptual framework for understanding the association between GDP growth and environmental pollution in recent years. The EKC specifies that as a country's economy grows, environmental pollution initially increases, but at a certain level it decreases [3]. Several investigations have been conducted globally to explore the EKC framework. Our literature review from 2016 to 2024 provides strong support for the EKC hypothesis across regions worldwide. For example, [4] established the EKC in “46 Sub-Saharan African countries”, while [5] discovered evidence from the European Union. Similarly, [6] validated the EKC in BRICS nations, and [7] found support in 39 developing countries. [8] verified the EKC in China. Conversely, the literature also contains studies that refute the EKC hypothesis. For instance, research by [9] on 25 African nations, [10] on 64 middle-income nations, [11] on the USA, and [12] on ASEAN-5 countries all failed to support the EKC framework in those contexts. Despite the extensive literature, empirical studies rigorously supporting the EKC hypothesis in MICs remain scant. The research gap highlights the need for further exploration into the unique economic-environmental dynamics of these countries. Subsequently, this study seeks to close this gap by determining the legitimacy of the EKC context in MICs, focusing on how GDP growth influences environmental outcomes during their transitional phase toward sustainable growth.

Renewable energy is often slow to provide a decisive solution to balancing energy needs and environmental sustainability, as it justifies energy demands without the adverse effects of carbon discharges [13]. Some studies have documented a significant adverse association between CO_2 emissions and renewable energy, including [14]. Conversely, some papers have designated a positive link between them. For instance, [15] revealed that expanding renewable energy infrastructure might paradoxically rise emissions due to energy-intensive production processes and the ongoing reliance on fossil fuels during the transition stage. Furthermore, some studies, such as [16], found no association between CO_2 releases and renewable energy, highlighting discrepancies in outcomes across regions. Therefore, the effect of renewable energy adoption on releases is context-specific and influenced by local dynamics. Significant potential assistance rises from switching to renewable energy sources, including wind, solar, and hydroelectric power, in MICs. Yet, the actual effect of renewable energy adoption on CO_2 emissions within the EKC framework remains empirically uninvestigated, particularly to understand its significant effects on these economies.

Some inquiries have examined the impact of renewable energy on CO_2 emissions in conjunction with FDI [17,18], innovation [19–21], and industrialization [22,23]. While much of the literature focuses on these variables individually, this study takes a more inclusive approach by analyzing their combined impact within the EKC framework, specifically for MICs. This integrated analysis provides deeper insights into how these variables affect environmental outcomes, addressing current research gaps that often overlook or incorporate the EKC framework. Therefore, using panel data from MICs, this research explores the nonlinear connection between GDP growth (captured by GDP per capita and its square) and CO_2 discharges. It also examines the impact of renewable energy and other economic factors. The results will assist nations in transitioning to a more sustainable growth model while addressing climate change.

Our inclusive literature review on the relationship between sustainable energy and CO_2 releases within and outside the EKC framework revealed mixed outcomes across contexts. Researchers have applied a range of econometric techniques, including OLS, Fixed Effects, Random Effects, Instrumental Variables, PMG, ARDL, NARDL, CS-ARDL, 2SLS, AMG, CCEMG, GMM, FMOLS, GLS, Quantile Regression, and DOLS. However, most of the literature relies on first-generation approaches, which are subject to ongoing criticism for producing unreliable outcomes due to their inability to address CD, a common problem in panel data analysis. First-generation models overlook CD, potentially providing biased estimates, a point of debate among researchers. Moreover, our review reveals that relatively few studies employ second-generation models better suited to effectively handle CD. Given this gap, the CCEMG and DCCE methods are the most suitable and latest second-generation techniques for addressing CD. Both methods accommodate heterogeneity and “unobserved common factors”, ensuring robust and unbiased estimates of the existence of CD, thereby enhancing the reliability of our findings in the context of renewable energy’s effect on CO_2 emissions.

Building on the above discussion, the primary objective of this investigation is to explore the integrated impact of FDI, innovation, and industrialization on CO_2 emissions in the EKC framework in MICs. Second, it assesses the effect of economic growth, captured by GDP per capita and its squared term, to test the EKC hypothesis. Third, the study examines the country- and group-specific heterogeneity effects of FDI, innovation, and industrialization on CO_2 emissions. Fourth, this paper aims to boost the robustness of the analysis by employing second-generation econometric techniques that account for CD and slope heterogeneity in estimating the factors of CO_2 emissions. Finally, this research explores the specific policy for a specific country as well as differentiated policies for upper- and lower-MICs, signifying tailored strategies to promote sustainable economic growth and facilitate low-carbon transitions based on the findings.

This study makes several unique contributions to the economics literature. First, this study offers new insights by examining the interactions among renewable energy, FDI, innovation, industrialization, and CO_2 emissions within the EKC framework. Second, this paper makes a contextual contribution by exploring the interplay among renewable energy, FDI, innovation, industrialization, and CO_2 emissions within the EKC framework in MICs, a context where such concurrent analysis is still inadequately explored. It also reports the variability between upper and lower MICs. Third, this study discloses that innovation displays a positive coefficient, indicating that existing innovation systems in MICs remain carbon-intensive (dirty). This outcome challenges basic concepts of technology's role in environmental protection in MICs and highlights the need to promote environmentally friendly innovation. Fourth, this study makes a methodological contribution by using second-generation estimators, such as the CCEMG and the DCCE, which account for CD and slope heterogeneity, thereby differing from traditional econometric methods. Finally, the study looks at economies at a very significant stage of development by focusing on MICs. It provides policymakers with useful information on how these countries can balance growth with environmental sustainability.

The subsequent portion of this study is prepared as follows: Section 2 delves into the pertinent theoretical and empirical literature. Section 3 details the data sources and methodological approach utilized in the analysis. Section 4 presents the empirical results, offering insights into the key findings, and Section 5 includes conclusions and policy recommendations.

2. Literature review

2.1. The environmental kuznets curve (EKC)

The EKC theory posits an inverted U-shaped relationship between environmental pollution and economic expansion, providing the theoretical foundation for this study. [24] originally proposed this theory, which holds that ecological decline rises with GDP growth in the initial stages of industrialization, urbanization, and energy consumption. However, as GDP rises, the income threshold is crossed, leading to higher demand for environmental quality and lower pollution levels. This shift is driven by technological advancements, economic structural changes, and enhanced regulatory frameworks that support cleaner production processes [25]. The EKC framework is especially pertinent for MICs, where economic growth and industrialization are accompanied by rising energy consumption and carbon emissions. This research employs the EKC hypothesis to analyze the collective effects of economic growth, renewable energy, FDI, innovation, and industrialization on CO_2 emissions in MICs, thereby laying the foundation for understanding potential trade-offs and policy measures.

2.2. Theoretical framework

To establish the theoretical underpinnings of our empirical models, we explicitly utilize the EKC, the Pollution Haven Hypothesis (PHH), and the pollution halo hypothesis. The EKC hypothesis posits an inverted U-shaped relationship between economic growth and environmental degradation. As income rises, pollution initially increases, then decreases once a threshold income level is reached. To incorporate this, our empirical model integrates GDP per capita and its squared term, consistent with the EKC framework.

Conversely, the Pollution Haven Hypothesis holds that countries with less stringent environmental regulations may attract more foreign direct investment (FDI), thereby increasing pollution. Some studies indicated that FDI could increase CO_2 emissions, driven by the "pollution haven hypothesis," especially in developing nations, where global firms transferred operations to jurisdictions with less stringent environmental regulations. For instance, [26] found that FDI increased CO_2 emissions in G7 nations. Similarly, [27] found that FDI led to higher emissions in "low-middle-high income and developing countries" and developing countries, often due to the influx of energy-intensive industries and fossil-fuel dependence in production processes. On the contrary, some studies highlight that FDI can positively influence environmental consequences by approving the transfer of green technologies and fostering cleaner production methods [28,29]. This viewpoint aligns with "the pollution halo hypothesis", which argues that FDI can explain progressive know-how and higher management practices, promoting eco-friendly development in the host state [30,39]. Therefore, our model contains FDI to examine how it affects CO_2 emissions, which aligns with these theories. This integration establishes the connections among economic activity, foreign direct investment, and environmental outcomes within established environmental-economic theories, providing justification for the variables under investigation and facilitating the interpretation of results.

2.3. Empirical literature

2.3.1. Renewable energy and CO_2 emission

The association between renewable energy use and CO_2 emissions within the context of the EKC hypothesis has received substantial attention in the current literature. Many studies on green energy use have found a robust negative relationship with CO_2 emissions, validating the EKC hypothesis that widespread adoption of renewable energy can significantly reduce environmental degradation [7]. For example, [5] explored the DOLS approach to examine the link between trade openness, real income, non-renewable and renewable energy, and CO_2 releases in the European Union between 1980 and 2012. According to the study, renewable energy and trade openness alleviated carbon discharges. Conversely, non-renewable energy intensified them, validating the EKC theory and indicating a two-way causal relationship between CO_2 emissions and renewable energy. Similarly, [31] focused on leading natural resource-dependent nations from 2000 to 2015, applied OLS, GLS, and GMM estimators, and found that renewable energy use reduced per capita CO_2 emissions. Also, their study highlighted the faster emissions reduction in countries with more robust institutional frameworks, confirming the EKC framework. Finally, [32] examined the relationship between economic complexity, natural resources, and sustainable development in EU nations from 1990 to 2019. Using the PMG-ARDL method, they discovered that economic complexity supports sustainable growth, whereas natural resources negatively affect it. Renewable energy positively impacts sustainable development, encouraging more investments. The study confirms the N-shaped EKC theory. The literature also discovered a connection between renewable energy and CO_2 releases, with some studies either not adopting the EKC hypothesis or failing to confirm its validity [33,34]. For instance, using the EKC hypothesis, [9] examined the influence of clean energy sources on carbon dioxide discharges in 25 chosen African nations between 1980 and 2012. Using panel cointegration analysis and robustness tests, the study found that clean energy negatively affected CO_2 emissions and that CO_2 emissions increased with income per capita, suggesting that the EKC hypothesis is unsupported. [35] employed a dynamic panel threshold model to display that renewable energy had a substantial adverse effect on CO_2 discharges only when consumption levels exceeded a specific threshold, a result more pronounced in developed nations with more vital institutions.

2.3.2. FDI and CO_2 emission

The literature has observed studies analyzing FDI, often alongside renewable energy consumption, to assess its effects on CO_2 emissions. For example, [36] discovered that tourism and FDI exacerbated CO_2 releases, while trade openness and real income mitigated environmental pollution, confirming the EKC hypothesis using data from 6 ASEAN nations from 1995 to 2018 using the panel ARDL method. Moreover, the appeal of FDI in terms of environmental destruction and sustainable development depends on factors such as the nature of the investment, the targeted industrial zones, and the host nation's ecological regulations [37]. Similarly, [38] examined the influence of FDI on energy intensity in developing nations from 1996 to 2019, using a GMM. The study found that FDI significantly lowers energy intensity. Policy recommendations were made to improve FDI's role in lowering energy intensity in these nations. Therefore, the impact of FDI on CO_2 releases is multifaceted and influenced by various relative factors.

2.3.3. Innovation and CO_2 emission

Innovation presents challenges and opportunities for reducing CO_2 emissions [39]. Early-stage industrial innovation can initially increase emissions, but low-carbon technologies have the potential to decrease environmental impacts in the long term [40]. Innovation is vital for advancing cleaner technologies, enhancing energy efficiency, and reducing emissions [41]. Several studies highlight the positive effect of innovation on reducing CO_2 emissions, especially in countries that invest in R&D and promote green technologies [42,43]. For instance, innovation has significantly enhanced energy efficiency and reduced emissions in BRICS nations [6]. However, its efficiency depends on the type and focus of innovation. Middle-income nations need policies that promote sustainable technologies within the EKC framework to foster innovation and reduce emissions. [44] investigated the asymmetrical effects of non-renewable and renewable energy and innovation on CO_2 discharges in Algeria. Using the NARDL and QARDL methodologies, the study found that positive shocks to renewable energy and innovation mitigated CO_2 emissions, while negative shocks to innovation exacerbated emissions. Likewise, [45] examined the dual effects of innovation shocks (beneficial and detrimental) on CO_2 emissions in 46 developing economies. The study found that positive innovation shocks reduce CO2 emissions, while negative shocks worsen the environment.

2.3.4. Industrialization, and CO_2 emission

Numerous studies have revealed positive and negative links between industrialization and environmental degradation. For example, [46] found that industrialization significantly increases CO_2 levels due to reliance on fossil fuels in engineering processes. Similarly, [47] emphasized that the rapid expansion of industrial sectors in developing nations often outpaces the adoption of green technologies, exacerbating carbon releases. On the other hand, [48,49] found that industrialization may lead to a decrease in CO_2 emissions under certain conditions. Their findings contradict the typical view that industrialization is synonymous with environmental degradation. Moreover, [50] revealed that although industrialization initially exacerbated environmental degradation, sustained economic growth later drove the adoption of cleaner technologies and reduced emissions, consistent with the EKC background. This transition toward environmental sustainability in industrial progress has drawn significant interest, particularly in MICs. Industrialization is a major source of CO_2 emissions in these nations, where energy-intensive industries often drive rapid economic growth. Balancing this growth with ecological sustainability remains an essential challenge. [51] found that industrialization increased CO_2 discharges, while renewable energy usage decreased them, confirming the EKC hypothesis. The negative interaction between green energy and industrial value-added suggested that green energy effectively offsets the environmental impact of industrialization. This conclusion was based on data from 2000 to 2018 and was derived using the GMM method.

2.3.5. Macroeconomic factors, and CO_2 emissions

[52] examined the association between CO_2 emissions, remittances, GDP, and renewable energy in G-20 nations. Using the FMOLS and DOLS models, they found that renewable energy use reduced carbon emissions, while GDP growth and financial development increased them. [16] used the NARDL method to assess the impact of nuclear energy, population growth, GDP growth, globalization, and renewable energy on CO_2 releases from 1985 to 2020. Their results indicated that globalization and GDP growth shocks increased emissions, while renewable energy had an insignificant impact, and nuclear energy shocks reduced emissions. Similarly, [53] inspected the relationships among FDI, economic growth (EG), renewable energy (RE), natural resources (NR), economic freedom (EF), and CO_2. Using CS-ARDL and panel quantile regression (PQR) for transition economies from 1998 to 2019, the study found a positive link between FDI and carbon emissions and a negative relationship between economic growth and CO_2 emissions. Equally, [54] investigated the impact of renewable energy, Chinese outward foreign direct investment (CoFDI), and energy intensity on CO_2 emissions in 46 nations that joined the Belt and Road Initiative, divided into European and Asian/MENA groups. Using the Driscoll–Kraay method, the results showed a pollution-halo effect in European countries, where FDI is beneficial for the environment. Conversely, CoFDI increased CO2 emissions in Asian/MENA nations, validating the EKC and pollution haven hypotheses. [55] examined the relationships among FDI, GDP, renewable energy, fossil fuel consumption, trade liberalization, and CO_2 in France from 1980 to 2023 using the ARDL approach. The study found that fossil fuels raised CO_2 emissions, while renewable energy dropped them, but FDI increased them. [56] examined the link among FDI, GDP, trade, globalization, and CO_2 emissions in the ten largest economies from 1981 to 2022. The results demonstrated a positive relationship between GDP and CO_2 emissions across all panels, supporting the EKC in an inverted U-shaped pattern. [57] examined the interconnections between GDP, FDI, innovation, renewable energy, trade openness, and CO_2 emissions in Slovakia. Using the ARDL method, the study found that renewable energy and innovation were associated with lower CO_2 intensity over time, whereas trade openness and FDI had different effects. [58] investigated the asymmetric effects of trade, economic growth, renewable energy, and innovation on CO_2 emissions in China from 1990 to 2023, employing an NARDL model. The study discovered that positive shocks in innovation and renewable energy lead to lower emissions, while negative shocks lead to higher emissions.

2.4. Gaps in empirical literature

The key research gaps include, first, the literature lacks an inclusive exploration of the combined impacts of renewable energy, FDI, innovation, and industrialization on CO_2 emissions within the EKC hypothesis, often neglecting their interactions. Second, existing studies have not thoroughly explored the interplay among renewable energy, FDI, innovation, industrialization, and CO_2 emissions within the EKC framework in MICs, thereby impeding understanding of their unique environmental and economic dynamics. Moreover, many studies neglect to consider the heterogeneity inherent between upper- and lower-middle-income nations. Third, this research provides a significant methodological gap in prevailing literature by employing second-generation econometric approaches, specifically the CCEMG and the DCCE, to offer a more precise analysis of the EKC for MICs. Prior studies mostly relied on first-generation econometric methods that may yield biased estimates due to the existence of CD in panel data, which is overlooked in earlier studies. Finally, existing studies do not inspect whether the dynamics of renewable energy and innovation generate carbon-intensive or environmentally friendly ('green') innovation. Therefore, this research addresses this gap by examining whether innovation in MICs fosters sustainable development and precisely evaluating its effect on CO_2 emissions, a rarely explored topic in the literature on innovation-environment dynamics.

3. Research design

3.1. Data

We utilize panel data from 25 middle-income countries (Appendix Table A3) spanning 27 years (1996 to 2022). We choose the countries based on the availability and accessibility of the data from the selected sources. Data on other MICs are unavailable for some important independent variables, so we are unable to include other countries from these income groups. For reporting variables in common logarithms, linear interpolation is used to fill in missing values. Logarithmic transformations exclude observations with zeros or negative values, but such cases are extremely rare in our sample because the study considers only 25 countries out of 110, confirming their minimal presence. However, in the context of the EKC theory, CO_2 discharges serve as the predicted variable, while renewable energy (RE) is the key predictor variable. GDP per capita (PCI) and its squared term (PCIS) are included to capture the EKC's prediction that environmental pollution initially increases with GDP growth before decreasing at higher levels of GDP. The control variables for CO_2 emissions are foreign direct investment (FDI), innovation (INNO), and industrialization (IND).

However, this study measures renewable energy (LRE) as the proportion of renewable energy in total final energy consumption, derived from World Bank data, with references to the studies of [59,60]. Correspondingly, for the control variables, firstly, net inflows of foreign direct investment (FDI) are measured in current US dollars. This study uses a logarithmic transformation to even out the data and address differences in scale. Using current USD values for FDI is consistent with previous panel data studies [61,62] that examined absolute FDI flows and their environmental impacts. Secondly, prior studies have used a diversity of innovation proxies, including R&D expenditures (RD), patents (PAT), trademarks (TM), R&D as a percentage of GDP, scientific and technical publications, etc. Common choices among these proxies include R&D expenditures [63,64]), patents [65,66], and trademarks [4]. Building on prior research that often relied on individual innovation indicators, we use a composite innovation index using "principal component analysis (PCA)," which includes R&D expenditure, patent records, and trademark records, to address the multicollinearity issue among innovation proxies in MICs. Employing "Bartlett's test of sphericity and the KMO (Kaiser–Meyer–Olkin) measure", we measure the sampling adequacy for PCA. The latter shows that factor extraction is possible because the underlying correlations are strong enough ($\chi2(3) = 1,389.08$, $p < 0.00$). While individual measures remain consistently strong, ranging from 0.67 to 0.83, the aggregate KMO statistic reaches 0.74, which is significantly higher than the 0.60 standard. Therefore, the innovation index is utilized as a significant control variable. Finally, the World Bank's measure of industrialization (IND) is the percentage of GDP attributable to industry's value added, which shows how economies are structured. Although it does not measure energy intensity by sector, it remains a common and widely accepted way to examine the relationship between industrial growth and environmental outcomes, such as CO_2 emissions [51,67].

Therefore, publicly available justifiable data sources are used for this study. The variables have been converted into their common logarithms to prevent potential issues with outliers. The following Table 1 demonstrates the data sources and their comprehensive overview:

3.2. Empirical model

In this paper, the selection of variables is carefully grounded in a comprehensive literature review, ensuring consistency with the EKC framework. CO_2 emissions are modeled as a function of renewable energy, while GDP per capita (PCI) and its squared (PCIS) are incorporated to capture the nonlinear relationship between economic growth and environmental impact. A set of control variables is also incorporated to strengthen the investigation. Therefore, the baseline regression model is specified as follows:

$$CO_2 \ = f(RE, PCI, PCIS, Z)\text{.......................} \ (1).$$

We transform equation (1) into equation (2) using the common logarithms on both sides. Subsequently, the resulting coefficients in the notation reflect the baseline model as follows:

$$LCO_{2it} \ = \alpha_0 + \beta_1 LRE_{it} + \beta_2 LPCI_{it} + \beta_3 LPCIS_{it} + \gamma Z_{it} + \varepsilon_{it}. \ .... \ (2).$$

Where ε it means the residual term, i means the country, t signifies time, α_0 represents the intercept and β_i displays the coefficients of the predictors. LCO_{2it} is the predicted variable, LRE_{it} is the explanatory independent variable, and LPCIit and LPCISit capture the nonlinear link. Z_{it} is the control variable matrix, including $LFDI_{it}$, $LINNO_{it}$, and $LIND_{it}$ to examine the EKC hypothesis. The EKC hypothesis is supported if $\beta1 > 0$ and $\beta2 < 0$, implying an inverted-U relationship. Given the quadratic specification in log10 income, the turning point is derived by differentiating with respect to LPCI, yielding:

$$LPCI^* = -\frac{\beta_1}{2\beta_2}$$

The corresponding income level in PPP-adjusted GDP per capita is obtained as:

$$LPCI_{pc^*} = 10^{-\beta_1/(2\beta_2)}$$

We use second-generation unit root tests, namely "the CIPS [70] and CADF [71] tests", to measure the stationarity of the variables in light of the cross-sectional dependency (CD) that has been established by the Pesaran CD [72] test. These tests determine whether the variables are stationary at levels or require differencing. After confirming stationarity, we investigate slope heterogeneity using the Blomquist and Westerlund [73] kernel-based HAC robust test, given the presence of CD. In addition, the present research employed the "panel cointegration test" proposed by [74] to assess the long-term relationships between carbon dioxide emissions and explanatory factors.

Finally, we use a second-generation panel data method to explore the relationship between CO_2 emissions and the explanatory variables using the CCEMG estimator proposed by [75]. This method is appropriate for heterogeneous panels characterized by CD and slope heterogeneity. The CCEMG approach accounts for unobserved common factors by augmenting each cross-sectional regression with cross-sectional averages of the dependent and explanatory variables, which act as proxies for these common shocks with heterogeneous loadings. Equation 3 shows the CCEMG specification:

$$y_{it} \ = \alpha_i + \beta_i' \chi_{it} + \gamma_{i0} \overline{y}_{it} + \Gamma'_{\ i0} \overline{\chi}_t + \varepsilon_{it}. \ .... \ (3).$$

where y_{it} denotes CO_2 emissions, χ_{it} is the vector of explanatory variables, and $\overline{y}_{it} = N^{-1}\sum_{i=1}^{N} y_{it}$ and $\overline{\chi}_{it} = N^{-1}\sum_{i=1}^{N} \chi_{it}$ are cross-sectional averages. The slope coefficients β_i are permitted to vary across nations, capturing slope heterogeneity. Estimation is conducted separately for each cross-sectional unit, and the overall CCEMG estimator is obtained as the simple mean of the individual country-specific estimates. Time fixed effects are not included separately, as the cross-sectional averages span the space of common time effects.

As a robustness check, we employ the DCCE estimator developed by [76], which extends the CCEMG framework to dynamic settings. The DCCE model accounts for persistence and dynamic adjustments by including lagged dependent variables and lags of cross-sectional averages. The dynamic equation (4) for the DCCE model is as follows.

$$y_{it} \ = \alpha_i + \rho_i y_{i,t-1} + \beta_i' \chi_{it} + \sum_{p=0}^{P} \gamma_{ip} \overline{y}_{t-p} + \sum_{p=0}^{P} \Gamma'_{\ ip} \overline{\chi}_{t-p} + \varepsilon_{it}. \ .... \ (4).$$

Where, Y_{it-1} captures the dynamic structure of emissions, and the lagged cross-sectional averages control for dynamic common factors.

The number of lags p is set to 3, consistent with the rule-of-thumb $P = [T^{\frac{1}{3}}]$ proposed by [76], which confirms consistent estimation in dynamic multifactor panel settings. The explanatory variables are considered weakly exogenous in relation to the idiosyncratic error term. Standard errors that are robust to heteroskedasticity are reported, and no other small-sample bias corrections or finite-sample adjustments are made.

Additionally, the "Dumitrescu-Hurlin (D-H) [77] panel causality test" is applied to ascertain the directionality of causal relationships among variables. A distinctive feature of this method is its ability to yield variations in coefficients across different cross-sections, thereby enabling a more comprehensive analysis of causal patterns. The D-H method is briefly explained in Equation 5.

$$Y_{it} \ = \beta_i + \sum_{i=1}^{k} \alpha_i Y_{i,t-k} + \sum_{i=1}^{k} \delta_i X_{i,t-k} + \varepsilon_{it}. \ .... \ (5).$$

Equation 6 clearly defines "the null and alternative hypotheses", with β_i the constant, δ_i the coefficient slope, and α_i representing the lag parameter.

$$H_0 : \ \delta_i \ = \ \delta_i \ = \ 0, H_i : \begin{cases} \delta_i = 0, \forall_i = 1, 2, \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots N \\ \delta_i \neq 0, \forall_i = N_1 + 1, N_1 + 2, \cdots\cdots\cdots\cdots .N \end{cases} . \ .... \ (6).$$

The alternative proposition posits that panel data analysis can discern at least one directional causal relationship, despite variations in Granger causality among different cross-sectional units.

Table 1

Sources and overview of data.

Vars	Description	Mean	Max	Min	SD	Obs	Source
LINNO	The Innovation Index consists of TM, PAT, and RD.	−0.002	5.571	−3.090	1.639	675	TM from [68]; PAT from [2], & RD from [69]
LCO_2	CO_2 emissions (metric tons per capita)	0.478	1.186	−0.493	0.364	675	[2]
LRE	% of final energy consumed that comes from renewable sources	1.081	1.850	−0.398	0.492	675	
LPCI	Current US$ per capita GDP values, converted by PPP	3.979	4.571	2.925	0.300	675	
LFDI	Net inflows of foreign direct investment (BoP, current US$)	9.465	11.977	6.669	0.898	675	
LIND	Industry (including construction), value added (% of GDP)	1.473	1.696	1.210	0.094	675	

Note: The common logarithm is used to report all variables.

4. Results and discussion

Firstly, the Pesaran CD test [72] is used to assess the interconnectivity of global economic data. Table 2 reveals that CD is present in all series. The analysis's variables are found to be interconnected, likely due to factors like globalization, international trade, and shared macroeconomic conditions. The following Table 2 represents the results from CD, URT, and SH tests:

Secondly, to report the CD problem, we utilized the CADF and CIPS tests. Table 2 provides detailed outcomes of unit root tests, including some cross-sections that are stationary at the level, while others require first differences to be stationary, indicating a mixed nature of stationary properties in variables. The results reveal that some variables remain constant at all levels (I(0)), while others become constant after first differencing (I(1)). It is important to note that none of the variables are integrated of order two, I(2), since all series become stationary at the first difference. So, the variables are either I(0) or I(1), which meets the requirements for [74] panel cointegration testing.

Moreover, we use the Blomquist-Westerlund [73] slope-heterogeneity test to determine whether the slope coefficients are equal across all cross-sectional units. The adjusted Delta statistics (10.21 and 12.63) are statistically significant at the 1% level, which means that the null hypothesis of slope homogeneity must be rejected (Table 2). This shows that the slopes differ across countries. The presence of heterogeneous slopes supports the application of second-generation mean-group estimators, such as the CCEMG and DCCE, which allow slope coefficients to differ across cross-sections while controlling for CD via common correlated effects.

Thirdly, the correlation matrix in Table 3 aligns with economic theory, revealing significant relationships between CO_2 emissions and the most manipulated variables. Most variables show positive correlations, but some exceptions exist. Moreover, Table 3 presents the results of the multicollinearity (VIF) test, indicating that the model shows no multicollinearity issues, with an average VIF of 2.32. The following Table 3 demonstrates the results from the correlation matrix and multicollinearity test:

Next, this study employs the cointegration tests suggested by [74] to explore the long-run relationships among the variables. The [74] error-correction-based cointegration test works with panels that have both I(0) and I(1) variables, as long as none of the variables are I(2). Therefore, the mixed integration orders in the panel do not undermine the cointegration analysis. Table 4 presents cointegration among the selected variables, indicating a long-term equilibrium relationship, as evidenced by robust bootstrap p-values. To obtain robust p-values in the presence of CD, bootstrap critical values are calculated via repeated replications that maintain CD during resampling. The following Table 4 shows the cointegration outcomes by Westerlund:

Finally, Table 5 presents the findings from the CCEMG method, exploring the relationship between CO_2 emissions and macroeconomic factors, mainly highlighting the EKC and the character of renewable energy. The current study revealed an inverted-U-shaped relationship between CO_2 emissions and GDP per capita (LPCI), consistent with the EKC hypothesis. The positive coefficient for LPCI (4.646***) indicates that higher income levels are associated with increased emissions in the early stages of economic growth. However, the negative coefficient of LPCIS (−0.561**) supports the EKC, indicating that beyond a particular level of GDP growth, higher income levels reduce CO_2 emissions, marking a turning point towards environmental improvements. The current findings align with the results of [4,5]. Additionally, [6] and [7] found similar results, emphasizing a consistent pattern across different contexts. Conversely, our findings differ from those of [9,12] due to regional contexts, methodological approaches, specific periods, and additional variables that influence the association between GDP expansion and ecological impact.

Table 2
CD, URT, and SH test outcomes.

Variable	Pesaran CD	CADF		CIPS	
		At level	First difference	At level	First difference
LCO_2	35.95***	−1.53	−3.02***	−1.35	−4.34***
LRE	4.57***	−1.57	−3.38***	−1.64	−4.36***
LPCI	86.51***	−1.98	−3.03***	−1.71	−3.83***
LFDI	47.46***	−2.31***	−4.27***	−2.88***	−5.48***
LINNO	62.48***	−2.36***	−3.24***	−2.18**	−4.515***
LIND	16.34***	−2.27***	−3.01***	−2.11*	−4.03***
Slope heterogeneity (SH) test					
		Delta		***p*-value**	
Adj.		10.21***		0.00	
		12.63***		0.00	

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

The significant positive coefficient for LPCI and the negative coefficient for LPCIS support the EKC turning point, confirming an inverted-U-shaped correlation within the EKC framework. Using the estimated coefficients, the implied turning point is calculated as:

$$LPCI^{*} = -\frac{4.646}{2(-0.561)} = 4.14$$

Converting this value into income levels yields:

$$LPCI_{pc^{*}} = 10^{4.14} \approx 13,800$$

So, the estimated turning point is a PPP-adjusted GDP per capita of about 13,800. This value is significant because it falls within the observed sample range of log GDP per capita (2.92–4.57), signifying that the EKC relationship holds economic significance for the countries in the panel. This means that after reaching an income level of about 13,800, higher economic growth is connected with lower CO_2 emissions, consistent with the EKC hypothesis.

The significant negative coefficient for renewable energy (−0.423***) strongly indicates that increased use of renewable energy is associated with reduced CO_2 emissions. Therefore, a 1% increase in the share of renewable energy reduces emissions by 0.423%, indicating that small increases in renewable energy can have a big effect on lowering CO_2 emissions. The finding highlights the status of transitioning to cleaner energy sources to reduce ecological degradation and achieve long-term, sustainable goals. The outcome also emphasizes green energy as a vital tool in fighting climate change and promoting sustainable energy in the future. This finding supports prior works by [14,52], emphasizing the effectiveness of renewable energy in reducing carbon discharges and its positive impact on environmental outcomes. However, this finding contradicts those of [78] who identified ambiguous or positive connotations between them.

The positive coefficient for FDI (0.00722*) indicates a slight tendency for FDI to raise CO_2 emissions. Industrial activities may drive the effect of FDI on CO_2 emissions in MICs, as investments often focus on resource- and energy-intensive sectors. This outcome aligns with [26,27] and supports the pollution haven hypothesis that FDI, particularly in resource-intensive industries, can exacerbate CO_2 emissions due to increased industrial activity. However, our outcomes depart from those of [29] and [30], who observed either neutral or negative associations, potentially attributable to the diverse nature of FDI across countries, sectors, and technological advancements.

The coefficient (0.0398***) specifies that while innovation boosts economic growth, it can also increase CO_2 emissions. The finding indicates that innovation is focused on traditional or non-ecological technologies, which may lead to higher energy consumption and emissions. It reproduces the scale and composition effects of economic and technological activities, where industrial growth and patenting in non-environmentally friendly sectors can compensate the benefits of cleaner technologies in the short term. However, the finding is similar to those of [42,43], likely reflecting the energy-intensive nature of early-

Table 3
Correlation matrix and multicollinearity test outcomes.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	VIF
(1) LCO_2	1.00						–
(2) LRE	−0.75***	1.00					1.40
(3) LPCI	0.60***	−0.33***	1.00				1.61
(4) LFDI	0.39***	−0.05	0.51***	1.00			3.98
(5) LINNO	0.46***	−0.19***	0.39***	0.82***	1.00		3.45
(6) LIND	0.24***	−0.33***	0.10**	0.18***	0.25***	1.00	1.18

* $p < 0.01$, ** $p < 0.05$.

Table 4
Westerlund's cointegration results.

	Value	Z-value	P-value	Robust P-value
Gt	−9.84***	−37.74	0.00	0.00
Ga	−0.43***	8.81	1.00	0.00
Pt	−13.55***	−1.56	0.05	0.00
Pa	−0.50***	6.48	1.00	0.00

Note: Robust p-values are bootstrap-based and account for CD. *** $p < 0.01$.

Table 5
The CCEMG estimations.

Variable	Coef.	S. E	z	*p*-value
LRE	−0.423***	0.099	−4.280	0.000
LPCI	4.646***	1.713	2.710	0.007
LPCIS	−0.561**	0.231	−2.430	0.015
LFDI	0.007*	0.004	1.790	0.073
LINNO	0.040***	0.015	2.740	0.006
LIND	0.162*	0.091	1.780	0.074
Cons	−5.383	4.119	−1.310	0.191
Wald x^2	49.10***			
RMSE	0.010			

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

stage innovations. However, our conclusion differs from that of [40,41], who found a negative association, possibly because of the long-term benefits of cleaner technologies.

The association between industrialization and rising CO_2 emissions is evident, as the energy-intensive nature of the industrial sector drives this growth, as reflected by the positive coefficient (0.162*). The expansion of industries often leads to a significant reliance on fossil fuels, resulting in environmental degradation and requiring substantial energy inputs in manufacturing and production. The outcomes align with [46,47], suggesting a potential link between industrialization and increased energy consumption and emissions. However, our outcomes diverge from those of [48,49] who observed a neutral or negative association.

Additionally, we conduct several additional analyses to ensure the robustness of our overall results, given insignificant findings across countries. Firstly, the DCCE estimator confirms reliable outcomes by eliminating CD and unobserved global shocks. It accounts for differences in slope across the 25 nations and corrects for the Nickell bias associated with dynamic panels, yielding more accurate long-run elasticities than regular estimators. The following Table 6 represents the DCCE estimations:

Table 6
The DCCE estimations.

Variable	Coef.	S. E	z	*p*-value
$L.LCO_2$	0.112**	0.055	2.02	0.043
LRE	−0.361***	0.071	−5.05	0.000
LPCI	5.630***	1.724	3.26	0.001
LPCIS	−0.642***	0.211	−3.05	0.002
LFDI	0.008*	0.004	1.78	0.075
LINNO	0.027***	0.009	2.79	0.001
LIND	0.196*	0.101	1.94	0.052
Cons	−11.394***	3.509	−3.25	0.001

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 6 demonstrates the outcomes of the DCCE estimation as a robustness analysis to validate the findings from the CCEMG method. The DCCE results largely align with the previous CCEMG estimates, confirming the significance of key variables in explaining CO_2 discharges. The coefficient for LRE remains adverse and highly significant (−0.361***), reinforcing its inverse association with CO_2 emissions. Similarly, LPCI has a positive and substantial influence, whereas the squared term (LPCIS) is negative and significant, supporting the EKC. Conversely, LFDI shows a positive, though marginally significant, effect on emissions (0.007*), consistent with previous findings, while innovation (LINNO) also shows a significant positive effect on emissions (0.040***). Equally, industrialization (LIND) contributes positively to emissions but with marginal significance. Moreover, the lagged CO_2 emissions ($L.LCO_2$) show a positive and significant relationship, indicating that past emissions contribute to current levels. However, the overall results are consistent with those derived from the CCEMG method, signifying the robustness and reliability of the estimated associations among the variables analyzed. However, to ensure the CCEMG and DCCE estimates are reliable, we conduct diagnostics, such as. After implementing the CCEMG model with cross-sectional averages, the Pesaran residual CD test yields $CD = 0.05$ ($p = 0.96$), representing no significant residual cross-sectional dependence. Then, model stability is assessed by altering the lag structure, confirming that the main outcomes remain consistent across different lag lengths. Results stability is also established through alternative lag lengths and sensitivity analyses that exclude influential countries, ensuring that reported coefficients are robust and not influenced by specific countries or model specifications.

Secondly, we utilize the D–H panel Granger causality test to analyze predictive relationships and temporal precedence among the variables. The D–H test results are presented in Appendix Table A1. The results show that most variables can predict each other in both directions. More specifically, CO_2 emissions (LCO_2) have two-way predictive relationships with renewable energy (LRE), GDP per capita (LPCI), GDP per capita squared (LPCIS), innovation (LINNO), and industrialization (LIND), indicating feedback dynamics and temporal interdependence rather than structural causality. On the other hand, FDI (LFDI) shows a one-way predictive relationship with CO_2 emissions, meaning that past FDI values can help predict emissions, but not the other way around. On the contrary, several additional unidirectional predictive relationships are identified (e.g., LIND → LFDI and LPCIS → LINNO), indicating temporal precedence rather than policy-relevant causal mechanisms. It is crucial to underscore that the D–H test measures predictive content derived from lag structure and does not ascertain structural or policy causation. Thus, the findings should be regarded as indicative of Granger causality and dynamic interdependence.

However, the group- and country-specific estimates show that the relationship between CO_2 emissions and key explanatory variables differs across the 25 MICs (Appendix Table A3). Renewable energy (LRE) always reduces CO_2 emissions, especially in Armenia, Brazil, China, Mexico, Serbia, Turkey, Egypt, Tajikistan, Tunisia, and Ukraine. GDP per capita (LPCI), on the other hand, tends to be associated with higher emissions in some countries, especially China and the Kyrgyz Republic, but this is not always the case. FDI has a mixed effect: Kazakhstan, Egypt, and Tunisia show a positive relationship with emissions, but other countries do not. Innovation (LINNO) increases emissions in some countries, especially Brazil, China, and Costa Rica, but the results differ across countries. Industrialization (LIND) is associated with higher CO_2 emissions in China, Malaysia, Iran, and Tunisia, indicating the extent to which industrial growth in these countries contributes to emissions.

Finally, we employ the CCEMG estimator to evaluate the impact of diverse explanatory variables on CO_2 emissions, and the overall results show a statistically significant average effect across countries. Still, many country-specific coefficients are not significant due to differences across countries and the nature of the time-series data. Therefore, we use the DCCE, DSUR, and DOLS estimators to ensure our outcomes are correct, where the DOLS and DSUR estimators are used to mitigate endogeneity (Appendix Table A2), and these estimators align with the main findings of the CCEMG estimate. In summary, all robustness checks confirm the main findings and show that the effects on CO_2 emissions in the sample countries are statistically significant.

5. Conclusions

This study explores the relationship between CO_2 emissions and various economic factors, focusing on the EKC hypothesis and the role of renewable energy in reducing environmental degradation. Utilizing panel data from MICs, we employ the CCEMG and the DCCE methods to ensure reliable findings amid CD. The analysis also incorporates "second-generation unit root tests, Westerlund cointegration tests, and the D-H causality test" to establish long-term relationships and causal links.

The empirical outcomes offer robust evidence on the magnitude of each determinant. Specifically, the CCEMG and DCCE estimates disclose that renewable energy exerts a significant negative influence on CO_2 emissions, with elasticities ranging from -0.36 to -0.42, indicating that a 1% rise in renewable energy reduces emissions by approximately 0.36–0.42%. The results also confirm the EKC hypothesis, as the coefficient for GDP per capita is positive and significant (elasticity of $+4.64$ to $+5.65$), while its square is negative and significant (-0.56 to -0.64), validating the inverted-U-shaped relationship. The derived elasticities recommend that while early economic growth increases environmental degradation, the transition toward a "turning point" is statistically evident across the panel. Significantly, renewable energy emerges as a primary mitigator; the assessed elasticities are consistently negative and highly significant across both models, indicating that a 1% increase in green energy adoption produces a substantial reduction in total emissions. Regarding the control variables, the analysis discloses a hierarchy of influence. Innovation and industrialization serve as robust drivers, maintaining statistical significance and positive coefficients across both estimation methods, indicating they are the dominant contributors to the emissions profile in MICs. Correspondingly, FDI shows a positive, though marginally significant, effect on CO_2 emissions. On the other hand, causality tests reveal that most variables are interlinked through bidirectional paths, which suggests that renewable energy adoption and economic growth are not only drivers of environmental change but are also influenced by the resulting shifts in emissions levels.

To effectively mitigate CO_2 emissions, the following suggestions should be considered: Firstly, based on the estimated negative correlation between renewable energy and CO_2 emissions (a 1% rise in renewable energy share decreases per capita emissions by roughly 0.42%), policymakers should adopt market-decoupling policies. Precisely, replacing fossil fuel support with targeted renewable energy funding in solar and wind infrastructure through feed-in tariffs and fossil fuel subsidy reforms to accelerate the sustainable clean energy transition. Secondly, to validate the EKC hypothesis, policymakers should pursue green growth strategies that accelerate the attainment of the EKC turning point, at which economic growth no longer increases CO_2 emissions. By focusing on policies that promote sustainable development, green technologies, and cleaner industries, policymakers can foster growth that aligns with emission reductions. Thirdly, since FDI exhibits marginal effects, countries should implement environmental screening mechanisms that attract clean technology FDI while discouraging pollution-intensive investments. Fourthly, the study reveals that innovation in MICs is associated with increased CO_2 emissions, with much of its carbon-intensive ('dirty') technological progress rather than green innovation. Therefore, policies should be put in place to promote environmentally sustainable innovation, such as incentives for technological progress focused on renewable energy, green patents, and clean technology R&D, to ensure that innovation contributes to reducing emissions. In addition, fostering the development of low-carbon technologies is crucial, as it enables nations to develop more efficient and scalable approaches to mitigate emissions. Finally, it is critical to implement policies that promote cleaner industrial practices, encouraging industries to adopt ecological technologies and reduce their carbon footprints. Moreover, policymakers should consider the entire lifecycle of renewable technologies to prevent environmental and economic challenges, thereby promoting sustainability and financial resilience.

Furthermore, policies should be tailored to each country's specific circumstances, given the fluctuating effects of CO_2 emissions across countries. The use of renewable energy is advised for all MICs, particularly in nations that are most severely affected by CO_2 emissions. Efforts to control FDI, innovation, and industrial growth should focus on ensuring that investments align with sustainable practices. This is especially important in countries such as China, Iran, and Tunisia, where industrialization is a major source of emissions. Innovation policies should focus on clean, low-carbon technologies to reduce rising emissions in Brazil, China, and Costa Rica. To effectively separate economic growth from emissions, it is important to have different strategies for upper- and lower-MICs.

Limitations of the study include a focus on only 25 MICs, which may limit the results' generalizability to other income groups of countries. Future research can explore various avenues to expand on the current findings. Firstly, the upcoming investigation should deliberately extend the examination to incorporate high- and low-income nations to compare the effects of economic factors across different contexts. Secondly, further study of renewable energy technologies in specific countries could offer a more comprehensive understanding of CO_2 emissions and sustainable development. Thirdly, future research should focus on large economies (such as BRICS) to identify specific impacts. Finally, investigating the interactions among GDP growth, technological advancements, and CO_2 emissions across industries could provide further insights.

CRediT authorship contribution statement

Md Zahidul Islam: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Md.Shamim Hossain:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammad Bin Amin:** Writing – original draft, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition. **Judit Oláh:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was supported by the University of Debrecen Program for Scientific Publication.

Appendix

Table A1
Pairwise D-Hurlin panel causality test outcomes.

SL	H_0	W-Stat.	Zbar-Stat.	P-value	Results
1	LRE → LCO$_2$	3.05***	5.88	0.00	LRE ↔ LCO$_2$
	LCO$_2$ → LRE	2.21***	3.35	0.00	
2	LPCI → LCO$_2$	4.70***	10.83	0.00	LPCI↔ LCO$_2$
	LCO$_2$ → LPCI	3.02***	5.77	0.00	
3	LPCIS → LCO$_2$	4.90***	11.43	0.00	LPCIS↔ LCO$_2$
	LCO$_2$ → LPCIS	2.93***	5.52	0.00	
4	LFDI → LCO$_2$	2.31***	3.64	0.00	LFDI→ LCO$_2$
	LCO$_2$ → LFDI	1.50	1.23	0.21	
5	LINNO → LCO$_2$	3.99***	8.68	0.00	LINNO↔ LCO$_2$
	LCO$_2$ → LINNO	2.21***	3.37	0.00	
6	LIND → LCO$_2$	4.60***	10.52	0.00	LIND ↔ LCO$_2$
	LCO$_2$ → LIND	5.46***	13.11	0.00	
7	LPCI → LRE	4.01***	8.71	0.00	LPCI ↔ LRE
	LRE → LPCI	2.39***	3.89	0.00	
8	LFDI → LRE	3.57***	7.43	0.00	LFDI ↔ LRE
	LRE → LFDI	2.26***	3.49	0.00	
9	LINNO → LRE	3.84***	8.24	0.00	LINNO ↔ LRE
	LRE → LINNO	2.03***	2.82	0.00	
10	LIND → LRE	3.91***	8.44	0.00	LIND ↔ LRE
	LRE → LIND	2.9***	5.68	0.00	
11	LPCIS → LRE	4.07***	8.94	0.00	LPCIS ↔ LRE
	LRE → LPCIS	2.27***	3.53	0.00	
12	LFDI → LPCI	1.77***	2.042	0.04	LFDI ↔ LPCI
	LPCI → LFDI	3.76***	8.00	0.00	
13	LINNO → LPCI	1.71**	1.85	0.06	LINNO ↔ LPCI
	LPCI → LINNO	2.27***	3.52	0.00	
14	LIND → LPCI	2.22***	3.37	0.00	LIND ↔ LPCI
	LPCI → LIND	2.88***	5.37	0.00	
15	LPCIS → LPCI	2.04***	2.84	0.00	LPCIS ↔ LPCI
	LPCI → LPCIS	1.93**	2.52	0.01	
16	LINNO → LFDI	3.31***	6.65	0.00	LINNO ↔ LFDI
	LFDI → LINNO	1.75**	1.98	0.04	
17	LIND → LFDI	2.33***	3.71	0.00	LIND → LFDI
	LFDI → LIND	1.16	0.22	0.82	
18	LPCIS → LFDI	3.69***	7.79	0.00	LPCIS ↔ LFDI
	LFDI → LPCIS	1.74**	1.95	0.04	
19	LIND → LINNO	3.46***	7.09	0.00	LIND ↔ LINNO
	LINNO → LIND	2.89***	5.40	0.00	
20	LPCIS → LINNO	2.24***	3.45	0.00	LPCIS → LINNO
	LINNO → LPCIS	1.62	1.60	0.10	
21	LPCIS → LIND	2.85***	5.28	0.00	LPCIS ↔ LIND
	LIND → LPCIS	2.07***	2.93	0.00	

Note: The results are based on lag 1. *** $p < 0.01$, ** $p < 0.05$.

Table A2
Robustness checks (DV: CO$_2$).

	DSUR				**DOLS**			
Variable	Coef	S. E	t-Stat	p-value	Coef	S. E	t-Stat	p-value
LRE	−0.47	0.02	−30.72	0.00	−0.27	0.03	−9.61	0.00
LPCI	1.22	0.36	3.37	0.00	0.94	0.33	2.80	0.01
LPCIS	−0.11	0.05	−2.40	0.02	−0.10	0.04	−2.47	0.01
LFDI	0.03	0.02	1.84	0.07	0.02	0.01	2.82	0.01
LINNO	0.04	0.01	5.00	0.00	0.06	0.01	5.31	0.00
LIND	−0.23	0.07	−3.21	0.00	0.38	0.06	6.67	0.00
Cons	−2.02	0.65	−3.11	0.00				

Note: Dynamic Seemingly Unrelated Regression (DSUR) and Dynamic Ordinary Least Squares (DOLS).

Table A3
Country-specific outcome (DV: CO_2).

SN	Country	LRE	LPCI	LPCIS	LFDI	LINNO	LIND
Upper Middle-Income Countries							
1	Argentina	−0.11 (0.11)	3.25 (4.01)	−0.35 (0.48)	0.01 (0.01)	0.02 (0.04)	−0.12 (0.13)
2	Armenia	−0.29*** (0.07)	−1.74 (7.42)	0.30 (0.97)	0.05 (0.04)	−0.03 (0.14)	0.59 (0.93)
3	Brazil	−0.85*** (0.13)	−2.12 (9.87)	0.37 (1.19)	−0.001 (0.02)	0.09** (0.04)	−0.13 (0.14)
4	Bulgaria	−0.18* (0.10)	−1.44 (4.80)	0.25 (0.60)	−0.03 (0.03)	0.12 (0.09)	0.39 (0.27)
5	China	−0.39*** (0.10)	−5.69*** (1.29)	0.73*** (0.17)	−0.001 (0.02)	0.04** (0.02)	1.08*** (0.39)
6	Colombia	−0.38* (0.20)	10.25 (8.04)	−1.14 (0.99)	0.02 (0.08)	0.05 (0.05)	0.54 (0.33)
7	Costa Rica	0.09 (0.22)	5.66 (8.06)	−0.57 (0.95)	0.02 (0.08)	0.10* (0.06)	0.52 (0.81)
8	Kazakhstan	−0.32** (0.15)	2.35 (9.22)	−0.38 (1.09)	0.04** (0.02)	0.28 (0.22)	−0.16 (0.36)
9	Kyrgyz Republic	−0.43** (0.20)	27.89* (16.45)	−3.99* (2.30)	0.01 (0.02)	0.10 (0.13)	−0.30 (0.20)
10	Malaysia	−0.02 (0.08)	6.30 (7.96)	−0.72 (0.95)	0.02 (0.11)	0.03 (0.06)	0.83** (0.40)
11	Mexico	−0.59*** (0.22)	10.43 (9.27)	−1.24 (1.12)	−0.01 (0.02)	0.03 (0.06)	0.35 (0.44)
12	Paraguay	−1.66** (0.74)	8.02 (20.56)	−0.84 (2.57)	0.01 (0.01)	0.03 (0.11)	0.74 (0.63)
13	Peru	−0.59* (0.32)	4.83 (12.33)	−0.42 (1.55)	0.02 (0.05)	0.12 (0.14)	−0.79* (0.46)
14	Russian Federation	−0.08 (0.32)	0.65 (2.12)	−0.05 (0.25)	−0.01 (0.01)	0.01 (0.03)	0.11 (0.18)
15	Serbia	−0.48*** (0.11)	4.03 (8.62)	−0.34 (1.09)	−0.02 (0.03)	0.09 (0.05)	−0.20 (0.29)
16	South Africa	−0.10 (0.16)	19.36 (42.78)	−2.41 (5.19)	0.01 (0.01)	−0.03 (0.11)	0.71* (0.41)
17	Thailand	0.01 (0.15)	5.70 (4.88)	−0.57 (0.63)	0.01 (0.01)	0.01 (0.03)	−0.20 (0.25)
18	Turkey	−0.47*** (0.10)	−1.39 (2.28)	0.17 (0.28)	−0.02 (0.01)	0.07 (0.04)	−0.17 (0.22)
Lower Middle-Income Countries							
19	Egypt	−0.36*** (0.10)	7.55 (5.00)	−0.94 (0.63)	0.02*** (0.01)	−0.03 (0.06)	−0.19 (0.14)
20	India	−0.58 (0.38)	11.53*** (4.20)	−1.59*** (0.58)	0.02 (0.02)	0.03 (0.08)	−0.29 (0.28)
21	Iran	0.01 (0.01)	−8.68 (6.15)	1.03 (0.73)	−0.02*** (0.05)	0.01 (0.01)	0.19*** (0.13)
22	Mongolia	−0.06 (10.07)	−0.48 (9.12)	0.14 (1.14)	0.01 (0.01)	−0.01 (0.06)	−0.03 (0.15)
23	Tajikistan	−2.07*** (0.30)	15.11 (14.15)	−2.20 (2.07)	0.01 (0.02)	0.01 (0.04)	0.09 (0.25)
24	Tunisia	−0.32*** (0.09)	6.24 (7.67)	−0.71 (0.98)	0.03*** (0.01)	−0.01 (0.03)	0.42*** (0.12)
25	Ukraine	−0.35*** (0.09)	−11.22* (5.98)	1.44* (0.74)	0.02 (0.01)	0.09 (0.07)	0.48 (0.31)

Note: Country-specific outcome from the CCEMG method.

Data availability

Data will be made available on request.

References

[1] Global Carbon Project. Fossil CO2 emissions at record high in 2023. *Accessed October 4, 2024*. https://globalcarbonbudget.org/fossil-co2-emissions-at-record-high-in-2023/..

[2] World Bank. World Development Indicators (WDI). World Bank. Retrieved from https://databank.worldbank.org/source/worlddevelopment-indicators#.

[3] Grossman GM, Krueger AB. Environmental impacts of a north American free trade agreement. National Bureau of Economic Research Working Paper 1991;No. 3914: doi:10.3386/w3914.

[4] Acheampong AO, Adams S, Boateng E. Do globalization and renewable energy contribute to carbon emissions mitigation in Sub-Saharan Africa? Sci Total Environ 2019;677:436–46. https://doi.org/10.1016/j.scitotenv.2019.04.353.

[5] Dogan E, Seker F. Determinants of CO2 emissions in the European Union: the role of renewable and non-renewable energy. Renew Energy 2016;94:429–39. https://doi.org/10.1016/j.renene.2016.03.078.

[6] Fu Q, Álvarez-Otero S, Sial MS, Comite U, Zheng P, Samad S, et al. Impact of renewable energy on economic growth and CO2 emissions—evidence from BRICS countries. Processes 2021;9(8). https://doi.org/10.3390/pr9081281.

[7] Haldar A, Sethi N. Effect of institutional quality and renewable energy consumption on CO2 emissions—An empirical investigation for developing countries. Environ Sci Pollut Res 2021;28(12):15485–503. https://doi.org/10.1007/s11356-020-11684-1.

[8] Zaland Z, İmamoğlu H. Revisiting the environmental Kuznets curve hypothesis in the context of renewable and non-renewable energy in China. Business & Management Studies: an International Journal 2024;12(2):240–52. https://doi.org/10.15295/bmij.v12i2.2672.

[9] Zoundi Z. CO2 emissions, renewable energy and the Environmental Kuznets Curve: a panel cointegration approach. Renew Sustain Energy Rev 2017;72:1067–75. https://doi.org/10.1016/j.rser.2016.10.018.

[10] Ehigiamusoe KU, Lean HH, Smyth R. The moderating role of energy consumption in the carbon emissions-income nexus in middle-income countries. Appl Energy 2020;261:114215. https://doi.org/10.1016/j.apenergy.2019.114215.

[11] Dogan E, Ozturk I. The influence of renewable and non-renewable energy consumption and real income on CO2 emissions in the USA: evidence from structural break tests. Environ Sci Pollut Res 2017;24(11). https://doi.org/10.1007/s11356-017-8786-y.

[12] Munir Q, Lean HH, Smyth R. CO2 emissions, energy consumption and economic growth in the ASEAN-5 countries: a cross-sectional dependence approach. Energy Econ 2020;85:104571. https://doi.org/10.1016/j.eneco.2019.104571.

[13] Dincer I. Renewable energy and sustainable development: a crucial review. Renew Sustain Energy Rev 2000;4(2):157–75. https://doi.org/10.1016/S1364-0321(99)00011-8.

[14] Dilanchiev A, Umair M, Haroon M. How causality impacts the renewable energy, carbon emissions, and economic growth nexus in the South Caucasus countries? Environ Sci Pollut Res 2024:1–17. https://doi.org/10.1007/s11356-024-29493-6.

[15] Bulut U. The impacts of non-renewable and renewable energy on CO2 emissions in Turkey. Environ Sci Pollut Res 2017;24:15416–26. https://doi.org/10.1007/s11356-017-9090-5.

[16] Rehman A, Alam MM, Ozturk I, Alvarado R, Murshed M, Işık C, et al. Globalization and renewable energy use: how are they contributing to upsurge the CO2 emissions? a global perspective. Environ Sci Pollut Res 2023;30(4):9699–712. https://doi.org/10.1007/s11356-022-22093-2.

[17] Iqbal A, Tang X, Rasool SF. Investigating the nexus between CO2 emissions, renewable energy consumption, FDI, exports and economic growth: evidence from BRICS countries. Environ Dev Sustain 2023;25(3):2234–63. https://doi.org/10.1007/s10668-022-02172-7.

[18] Awan A, Abbasi KR, Rej S, Bandyopadhyay A, Lv K. The impact of renewable energy, internet use and foreign direct investment on carbon dioxide emissions: a method of moments quantile analysis. Renew Energy 2022;189:454–66. https://doi.org/10.1016/j.renene.2022.02.146.

[19] Khan H, Weili L, Khan I. Examining the effect of information and communication technology, innovations, and renewable energy consumption on CO2 emission: evidence from BRICS countries. Environ Sci Pollut Res 2022;29(31):47696–712. https://doi.org/10.1007/s11356-022-19799-2.

[20] Khattak SI, Ahmad M, Khan ZU, Khan A. Exploring the impact of innovation, renewable energy consumption, and income on CO2 emissions: new evidence from the BRICS economies. Environ Sci Pollut Res 2020 Apr;27(12):13866–81. https://doi.org/10.1007/s11356-020-07876-4.

[21] Rahman MM, Alam K, Velayutham E. Reduction of CO2 emissions: the role of renewable energy, technological innovation and export quality. Energy Rep 2022;8:2793–805. https://doi.org/10.1016/j.egyr.2022.02.199.

[22] Rahman MM, Alam K. Impact of industrialization and non-renewable energy on environmental pollution in Australia: do renewable energy and financial development play a mitigating role? Renew Energy 2022;195:203–13. https://doi.org/10.1016/j.renene.2022.05.099.

[23] Wang W, Rehman MA, Fahad S. The dynamic influence of renewable energy, trade openness, and industrialization on the sustainable environment in G-7 economies. Renew Energy 2022;198:484–91. https://doi.org/10.1016/j.renene.2022.07.011.

[24] Grossman GM, Krueger AB. Economic growth and the environment. Q J Econ 1995;110(2):353–77. https://doi.org/10.2307/2118443.

[25] Shobande O, Asongu S. The rise and fall of the energy-carbon Kuznets curve: evidence from Africa. Management of Environmental Quality: an International Journal 2022;33(2):390–405. https://doi.org/10.1108/MEQ-05-2021-0118.

[26] Ren X, An Y, He F, Goodell JW. Do FDI inflows bring both capital and CO2 emissions? evidence from non-parametric modelling for the G7 countries. International Review of Economics & Finance 2024;95:103420. https://doi.org/10.1016/j.iref.2023.103420.

[27] Essandoh OK, Islam M, Kakinaka M. Linking international trade and foreign direct investment to CO2 emissions: any differences between developed and developing countries? Science of the Total Environment 2020;712:136437. https://doi.org/10.1016/j.scitotenv.2019.136437.

[28] Demena BA, Afesorgbor SK. The effect of FDI on environmental emissions: evidence from a meta-analysis. Energy Policy 2020;138:111192. https://doi.org/10.1016/j.enpol.2019.111192.

[29] Abbasi MA, Nosheen M, Rahman HU. An approach to the pollution haven and pollution halo hypotheses in asian countries. Environmental Science and Pollution Research 2023;30(17):49270–89. https://doi.org/10.1007/s11356-023-27620-3.

[30] Dagar V, Ahmed F, Waheed F, Bojnec Š, Khan MK, Shaikh S. Testing the pollution haven hypothesis with the role of foreign direct investments and total energy consumption. Energies 2022;15(11):4046. https://doi.org/10.3390/en15114046.

[31] Szetela B, Majewska A, Jamroz P, Djalilov B, Salahodjaev R. Renewable energy and CO2 emissions in top natural resource rents depending countries: the role of governance. Frontiers in Energy Research 2022;10:872941. https://doi.org/10.3389/fenrg.2022.872941.

[32] Zhang C, Zhang L. The relationship between toxic air pollution, health expenditure, and economic growth in the European Union: fresh evidence from the PMG-ARDL model. Environmental Science and Pollution Research 2024 Mar;31(14):21107–23. https://doi.org/10.1007/s11356-024-32342-w.

[33] Saidi K, Omri A. Reducing CO2 emissions in OECD countries: do renewable and nuclear energy matter? Progress in Nuclear Energy 2020;126:103425. https://doi.org/10.1016/j.pnucene.2020.103425.

[34] Dong K, Dong X, Dong C. Determinants of the global and regional CO2 emissions: what causes what and where? Applied Economics 2019;51(46):5031–44. https://doi.org/10.1080/00036846.2019.1606414.

[35] Chen C, Pinar M, Stengos T. Renewable energy and CO2 emissions: New evidence with the panel threshold model. Renewable Energy 2022;194:117–28. https://doi.org/10.1016/j.renene.2022.05.124.

[36] Pata UK, Dam MM, Kaya F. How effective are renewable energy, tourism, trade openness, and foreign direct investment on CO2 emissions? an EKC analysis for ASEAN countries. Environmental Science and Pollution Research 2023;30(6):14821–37. https://doi.org/10.1007/s11356-022-23094-3.

[37] Wu Y, Wang R, Wang F. Exploring the role of foreign direct investment and environmental regulation in regional ecological efficiency in the context of sustainable development. Sustainability 2023 Jun 5;15(11):9104. https://doi.org/10.3390/su15119104.

[38] Kasimov I, Wencong L, Saydaliev HB. Unlocking the potential of foreign direct investment to reduce energy intensity. Environmental Science and Pollution Research 2023 Jun;30(30):75382–400. https://doi.org/10.1007/s11356-023-27525-w.

[39] Mongo M, Belaïd F, Ramdani B. The effects of environmental innovations on CO2 emissions: Empirical evidence from Europe. Environmental Science & Policy 2021;118:1–9. https://doi.org/10.1016/j.envsci.2021.01.007.

[40] Zhang Y, Chen X. Spatial and nonlinear effects of new-type urbanization and technological innovation on industrial carbon dioxide emission in the Yangtze River Delta. Environmental Science and Pollution Research 2023;30(11):29243–57. https://doi.org/10.1007/s11356-023-27429-6.

[41] Tang W, Mai L, Li M. Green innovation and resource efficiency to meet net-zero emission. Resources Policy 2023;86:104231. https://doi.org/10.1016/j.resourpol.2023.104231.

[42] Chen Y, Lee CC. Does technological innovation reduce CO2 emissions? Cross-Country Evidence Journal of Cleaner Production 2020;263:121550. https://doi.org/10.1016/j.jclepro.2020.121550.

[43] Jiang Y, Hossain MR, Khan Z, Chen J, Badeeb RA. Revisiting research and development expenditures and trade-adjusted emissions: Green innovation and renewable energy R&D role for developed countries. Journal of the Knowledge Economy 2024;15(1):2156–91. https://doi.org/10.1007/s13132-023-01160-2.

[44] Bergougui B. Moving toward environmental mitigation in Algeria: Asymmetric impact of fossil fuel energy, renewable energy and technological innovation on CO2 emissions. Energy Strategy Reviews 2024;51:101281. https://doi.org/10.1016/j.esr.2023.101281.

[45] Weimin Z, Chishti MZ, Rehman A, Ahmad M. A pathway toward future sustainability: assessing the influence of innovation shocks on CO2 emissions in developing economies. Environment, Development and Sustainability 2022 Apr;24(4):4786–809. https://doi.org/10.1007/s10668-021-01634-3.

[46] Liu X, Bae J. Urbanization and industrialization impact on CO2 emissions in China. Journal of Cleaner Production 2018;172:178–86. https://doi.org/10.1016/j.jclepro.2017.10.156.

[47] Dong F, Wang Y, Su B, Hua Y, Zhang Y. The process of peak CO2 emissions in developed economies: a perspective of industrialization and urbanization. Resources, Conservation and Recycling 2019;141:61–75. https://doi.org/10.1016/j.resconrec.2018.10.003.

[48] Wang Q, Su M. The effects of urbanization and industrialization on decoupling economic growth from carbon emission–a case study of China. Sustainable Cities and Society 2019;51:101758. https://doi.org/10.1016/j.scs.2019.101758.

[49] Raheem ID, Ogebe JO. CO2 emissions, urbanization and industrialization: evidence from a direct and indirect heterogeneous panel analysis. Management of Environmental Quality: an International Journal 2017;28(6):851–67. https://doi.org/10.1108/MEQ-09-2016-0062.

[50] Aslam B, Hu J, Hafeez M, Ma D, AlGarni TS, Saeed M, et al. Applying environmental Kuznets curve framework to assess the nexus of industry, globalization, and CO2 emission. Environmental Technology & Innovation 2021;21:101377. https://doi.org/10.1016/j.eti.2020.101377.

[51] Mentel G, Tarczyński W, Dylewski M, Salahodjaev R. Does renewable energy sector affect industrialization-CO2 emissions nexus in Europe and Central Asia? Energies 2022;15(16):5877. https://doi.org/10.3390/en15165877.

[52] Jamil K, Liu D, Gul RF, Hussain Z, Mohsin M, Qin G, et al. Do remittance and renewable energy affect CO2 emissions? an empirical evidence from selected G-20 countries. Energy & Environment 2022;33(5):916–32. https://doi.org/10.1177/0958305X211070974.

[53] Wencong L, Kasimov I, Saydaliev HB. Foreign direct investment and renewable energy: examining the environmental Kuznets curve in resource-rich transition economies. Renewable Energy 2023 May;1(208):301–10. https://doi.org/10.1016/j.renene.2023.03.054.

[54] Liu P, Ur Rahman Z, Jóźwik B, Doğan M. Determining the environmental effect of Chinese FDI on the Belt and Road countries CO2 emissions: an EKC-based assessment in the context of pollution haven and halo hypotheses. Environmental Sciences Europe 2024 Mar 4;36(1):48. https://doi.org/10.1186/s12302-024-00866-0.

[55] Xuan VN. Determinants of carbon dioxide emissions in France. Environmental and Sustainability Indicators 2025 Nov;12:101032. https://doi.org/10.1016/j.indic.2025.101032.

[56] Wani MJ, Loganathan N, Alamir IA, Mujalli A, Almgrashi A. Examining the emissions-growth nexus: carbon impact, economic expansion, FDI, globalization, and trade in leading economies. Journal of Applied Economics. 2025 Dec 31;28(1):2554712. 2. doi:10.1080/15140326.2025.2554712.

[57] Nguyen TL, Luong HG, Xuan VN. Relationship between GDP, FDI, Renewable Energy, Trade Openness, Innovation, and CO2 in Slovakia: New Insights from ARDL Methodology. Environmental and Sustainability Indicators 2025 Dec;22:101102. https://doi.org/10.1016/j.indic.2025.101102.

[58] Chung DT, Xuan VN, Hoa PX. Asymmetric roles of innovation and renewable energy in shaping carbon emissions in China. Environmental and Sustainability Indicators 2026 Jan;26:101145. https://doi.org/10.1016/j.indic.2026.101145.

[59] Mukhtar M, Abdulqadir IA, Abubakar HS. Renewable Energy transition and Sustainable Economic Growth in South Asia: Insights from the CO2 Emissions Policy Threshold. Sustainability 2025;17(20):9289. https://doi.org/10.3390/su17209289.

[60] Huseynov A, Gezdim SB. The Impact of Renewable and Non-Renewable Energy Consumption on CO2 Emissions in Türkiye: evidence from Augmented ARDL Approach. Journal of Sustainable Development Issues 2024;2(2):89–103. https://doi.org/10.62433/josdi.v2i2.28.

[61] Abdouli M, Hammami S. The impact of FDI inflows and environmental quality on economic growth: an empirical study for the MENA countries. Journal of the Knowledge Economy 2017;8(1):254–78. https://doi.org/10.1007/s13132-023-01606-0.

[62] Phuc DN. The impact of foreign direct investment, trade openness, technological innovation and industrial sector performance on economic growth in Vietnam. Journal of Posthumanism 2025;5(6):14–28. https://doi.org/10.63332/joph.v5i6.1947.

[63] Nguyen TT, Pham TAT, Tram HTX. Role of information and communication technologies and innovation in driving carbon emissions and economic growth in selected G-20 countries. Journal of Environmental Management 2020;261:110162. https://doi.org/10.1016/j.jenvman.2020.110162.

[64] Islam MZ, Rahaman SH, Chen F. How do R&D and remittances affect economic growth? evidence from middle-income countries. Heliyon 2024;10(9). https://doi.org/10.1016/j.heliyon.2024.e30160.

[65] Ordeñana X, Vera-Gilces P, Zambrano-Vera J, Jiménez A. The effect of high-growth and innovative entrepreneurship on economic growth. Journal of Business Research 2024;171:114243. https://doi.org/10.1016/j.jbusres.2023.114243.

[66] Bucci A, Carbonari L, Gil PM, Trovato G. Economic growth and innovation complexity: an empirical estimation of a Hidden Markov Model. Economic Modelling 2021;98:86–99. https://doi.org/10.1016/j.econmod.2021.02.006.

[67] Islam MZ, Hossain MS, Amin MB, Ahamed MM, Oláh J. The asymmetric impacts of remittances on innovation in middle-income economies: a nonlinear autoregressive distributed lag approach. Journal of Innovation & Knowledge 2025;10(6):100817. https://doi.org/10.1016/j.jik.2025.100817.

[68] WIPO. The World Intellectual Property Organization. WIPO. Retrieved from https://www3.wipo.int/ipstats/key-search/indicator.

[69] UNESCO. United Nations Educational, Scientific and Cultural Organization. UNESCO. Retrieved from http://data.uis.unesco.org/Index.aspx?DataSetCode=SCN_DS&lang=en.

[70] Pesaran MH, Smith V, Yamagata T. Panel unit root tests in the presence of a multifactor error structure. Cambridge University, unpublished working paper, September 2009.

[71] Pesaran MH. A simple panel unit root test in the presence of cross-section dependence. Journal of Applied Econometrics 2007;22(2):265–312. https://doi.org/10.1002/jae.951.

[72] Pesaran MH. General diagnostic tests for cross-section dependence in panels. IZA Discussion Paper No. 1240, Institute of Labor Economics 2004.

[73] Blomquist J, Westerlund J. Testing slope homogeneity in large panels with serial correlation. Economics Letters 2013 Dec 1;121(3):374–8. https://doi.org/10.1016/j.econlet.2013.09.012.

[74] Westerlund J. Testing for error correction in panel data. Oxford Bulletin of Economics and Statistics 2007;69(6):709–48. https://doi.org/10.1111/j.1468-0084.2007.00477.x.

[75] Pesaran MH. Estimation and inference in large heterogeneous panels with a multifactor error structure. Econometrica 2006;74(4):967–1012. https://doi.org/10.1111/j.1468-0262.2006.00692.x.

[76] Chudik A, Pesaran MH. Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors. Journal of Econometrics 2015 Oct 1;188(2):393–420. https://doi.org/10.1016/j.jeconom.2015.03.007.

[77] Dumitrescu EI, Hurlin C. Testing for Granger non-causality in heterogeneous panels. Economic Modelling 2012;29(4):1450–60. https://doi.org/10.1016/j.econmod.2012.02.014.

[78] Khezri M, Heshmati A, Khodaei M. Environmental implications of economic complexity and its role in determining how renewable energies affect CO2 emissions. Applied Energy 2022;306:117948. https://doi.org/10.1016/j.apenergy.2021.117948.