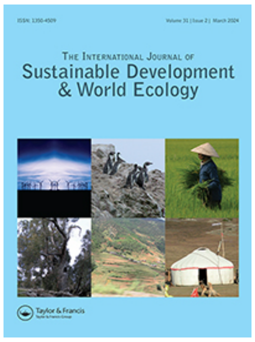

International Journal of Sustainable Development & World Ecology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tsdw20

Green innovation, foreign investment and carbon emissions: a roadmap to sustainable development via green energy and energy efficiency for BRICS economies

Queling Zeng, Mehmet Akif Destek, Zeeshan Khan, Ramez Abubakr Badeeb & Changyong Zhang

To cite this article: Queling Zeng, Mehmet Akif Destek, Zeeshan Khan, Ramez Abubakr Badeeb & Changyong Zhang (2024) Green innovation, foreign investment and carbon emissions: a roadmap to sustainable development via green energy and energy efficiency for BRICS economies, International Journal of Sustainable Development & World Ecology, 31:2, 191-205, DOI: 10.1080/13504509.2023.2268569

To link to this article: https://doi.org/10.1080/13504509.2023.2268569

Published online: 01 Nov 2023.

INTERNATIONAL JOURNAL OF SUSTAINABLE DEVELOPMENT & WORLD ECOLOGY
2024, VOL. 31, NO. 2, 191–205
https://doi.org/10.1080/13504509.2023.2268569

Green innovation, foreign investment and carbon emissions: a roadmap to sustainable development via green energy and energy efficiency for BRICS economies

Queling Zeng[a], Mehmet Akif Destek[b,c], Zeeshan Khan[d], Ramez Abubakr Badeeb[e] and Changyong Zhang[f]

[a]School of Artificial Intelligence, Guangdong Mechanical & Electrical Polytechnic, Guangzhou, China; [b]Department of Economics, Gaziantep University, Gaziantep, Turkey; [c]Adnan Kassar School of Business, Lebanese American University, Beirut, Lebanon; [d]Faculty of Business, Curtin University, Miri, Sarawak, Malaysia; [e]Faculty of Art and Social Sciences, Nottingham University Business School, Jalan Broga, Semenyih, Malaysia; [f]Department of Accounting, Finance and Economics, Faculty of Business, Curtin University, Miri, Sarawak, Malaysia

ABSTRACT

In contemporary times, emerging economies are intended to achieve higher economic growth via foreign direct investment and technological innovation. However, due to increased environmental challenges, these economies are adopting green energy as the key source of environmental recovery and net zero emissions. The present study investigates the influence of FDI, technological innovation, green energy, and trade on carbon emissions in BRICS economies during 1990–2022. This study also considers the role of economic expansion in identifying the environmental Kuznets curve (EKC). Using several panel diagnostic and cointegration tests, this study validates the slope heterogeneity and the existence of the cointegration between variables. Due to the non-normal data dispersion, this study uses novel moments quantile regression, while bootstrap quantile regression is used for the robustness. The results examined asserted the presence of the EKC hypothesis in the region, where the initial growth enhances emissions while after reaching at a threshold level, the emission level tends to reduce and environmental quality improves. Besides, this study observed that foreign trade and technological innovation are the key drivers of environmental degradation as these indicators significantly enhances pollution emissions. In contrast, foreign investment, energy efficiency, renewable electricity output, and renewable's consumption significantly improve environmental quality by declining carbon emissions. Following the empirical results, the policy recommendations asserted enhanced investment in renewable and energy efficiency sectors while attracting more foreign investment for sustainable development.

ARTICLE HISTORY
Received 7 August 2023
Accepted 5 October 2023

KEYWORDS
Foreign direct investment; green energy; environmental Kuznets curve; trade; technological innovation; carbon emissions

1. Introduction

The correlation between economic expansion/growth (GDP) and climatic change has been extensively investigated within sustainability, environmental, and energy economics. Numerous studies have explored this relationship, including Bashir et al. (2023); Gu et al. (2023); Ali et al. (2022); Balsalobre-Lorente et al. (2022); Leitão et al. (2021). There is a significant interconnection between two distinct categories of empirical research: the environmental Kuznets curve (EKC) and the causes of economy's development. The experimental investigations have provided explanations for these two relationships by examining variables including foreign direct investment (FDI), foreign trade, renewable energy, and emissions of pollutants. Furthermore, these studies have been implemented in various nations or regions, using various econometric methodologies such as panel or time series analysis.

The BRICS economies have considerable importance due to their substantial share of the global population and economic productivity. As these countries undergo a period of rapid urbanization and industrialization, they are concurrently confronted with the challenging task of ensuring environmental sustainability, with a specific focus on mitigating carbon emissions (CO2e) (Qing et al. 2023). Since the BRICS countries are in the take-off situation in the economic growth's perspective. Therefore, industrial and economic activities have been enhanced, mostly dependent on fossil fuel consumption, leading to higher CO2e. From Figure 1, it can be observed that the level of CO2e persistently rises. However, China remains the top-emitting economy within the group economies, followed by India and Russia. Still, over the years, the level of emissions has increased in China and India, while Russia has reduced the level of CO2e.

CONTACT Mehmet Akif Destek adestek@gantep.edu.tr Department of Economics, Gaziantep University, Adnan Kassar School of Business, Gaziantep 1102-2801, Turkey

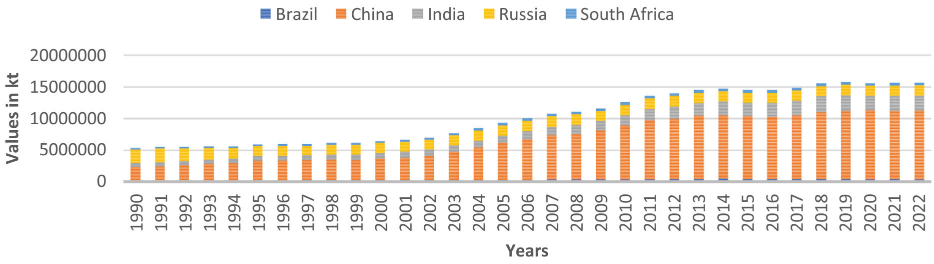

Figure 1. Carbon emissions in BRICS economies.

In accordance with Yabuki (2018), the production sector and FDI activities are widely recognized as crucial factors influencing economic expansion. Moreover, it has been recognized that industrial activities have a significant role in driving the economy's expansion. Similarly, FDI plays a substantial part in expanding the industrial sector in BRICS nations. This is achieved by attracting foreign resources via offshore operations or relocating manufacturing activity from advanced nations to the BRICS economies. The increase in industrial production via manufacturing operations results in a significant demand for energy consumption, identified as one of the primary suppliers of the emission of pollutants (Shahbaz et al. 2015). Nevertheless, this disclosure has meaningful implications for the development of the economy as well as the environment. Moreover, the influx of FDI to the BRICS countries can influence CO2e via many channels, including scale, technique, and structural impacts (Bakhsh et al. 2017). However, the empirical literature widely addresses the influence of FDI on economic output. Still, a crucial question remains unresolved from the perspective of the BRICS economies: what is the impact FDI on the quality of the environment in the BRICS regions? This question motivates the present study to empirically examine the true connection between the FDI and CO2e, as the existing literature offers contradictory evidence depending on the nature and growth of different economies.

The primary source of CO2e is attributed to burning fossil fuels and industrial activities (Destek and Sarkodie 2019). Numerous scholarly investigations have explored the determinants of CO2e (Sadorsky 2012), and discovered multiple factors that contribute to the significant increase in CO2e. These variables include but are not limited to economic development, trade, technological progress, foreign investments, etc. Various international accords have been established to mitigate global warming, such as the Paris Climate Agreement (PCA) in 2015 and the Kyoto Protocol 1997. Despite the existence of climatic change control agreements, the phenomenon of global warming continues to exhibit an upward trend (Khan et al. 2020). In response to these agreements, economies have invested and expanded their renewable energy sources, the key indicator of environmental recovery (Shahzad et al. 2021; Cai et al. 2022). In the context of the BRICS economies, it can be observed that the generation of renewable electricity and consumption of renewable energy have volatile trends during the last few decades (see Figure 2). However, Brazil remains at the top of the list in generating and consuming environmentally friendly energy, followed by India. Still, the exact influence of these variables remains a puzzle in

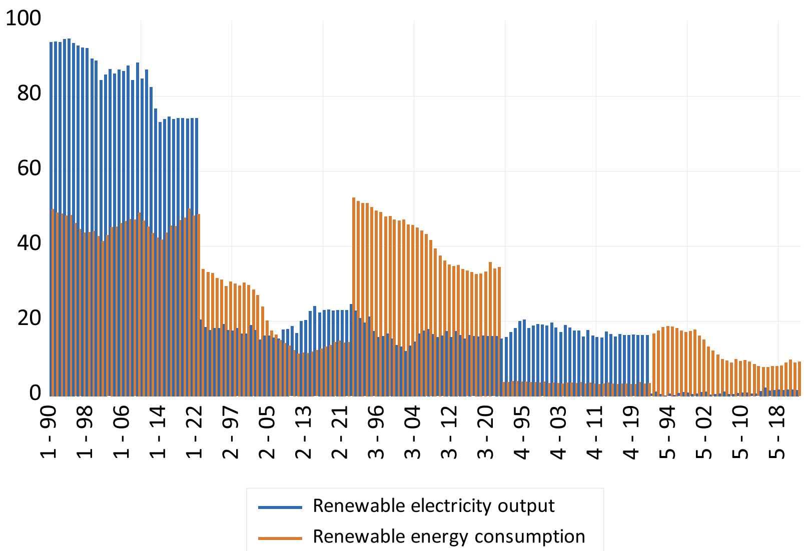

Figure 2. Green energy in BRICS economies.

the context of the BRICS, which leads this study to a substantial research question: are renewable energy production and consumption favorable for environmental sustainability? If so, what is the exact magnitude of the influence? Appropriate empirical analysis is needed to answer these questions, which motivates this research to examine emerging economies to provide relevant and attractive policy measures for tackling environmental issues.

Following the backdrop, the present study develops the following objectives, which must be accomplished to restructure environmental recovery and sustainability policies. Firstly, the current research examines the influence of FDI on the environmental quality – measured as CO2e in the BRICS economies. Since majority of the experimental studies have been done on discovering the important role of FDI in economic development (Popescu 2014; Pegkas 2015). Recently, the economies have been more concerned about environmental recovery, which addressed the vitality of examining the influence of FDI on environmental quality. Secondly, this study tends to analyze the impact of economic expansion on environmental quality. Studies in majority have mentioned its importance in the economic and environmental quality. Therefore, the present study also uses quadratic economic growth to examine the EKC's existence in the selected region. Nonetheless, the BRICS economies are improving their renewable production and consumption. Therefore, the third objective of this research is to empirically scrutinize whether renewable electricity output and renewable energy consumption influence environmental quality. Moreover, this research also considers the important role of energy efficiency, foreign trade, and technological innovation in the empirical analysis. The BRICS economies hold substantial population and economic power, improving their trading and technical capacity. To achieve these objectives, the present research uses novel panel estimation approaches to attain robust empirical results.

This research is novel and makes a valuable contribution to the persistent literature strand in the following ways: Unlike other studies that focus on isolating certain aspects, the present study adopts a comprehensive perspective by concurrently examining various elements, including FDI, GDP, energy efficiency, renewable energy, trade, and technological advancement. A more thorough study is provided on the intricate nature of CO2e within the BRICS economies by simultaneously examining these elements. Although the BRICS countries hold a substantial share of the global economy, a scarcity of comprehensive studies that extensively examine the distinct environmental concerns and possibilities associated with this group exists. This research addresses the aforementioned void by concentrating only on the BRICS economies. This research offers a valuable input to the continuing discourse on the correlation between economic growth and the sustainability of the environment by investigating the validity of the EKC hypothesis within the BRICS countries. The findings of this study provide empirical evidence that supports the validity of the EKC hypothesis while also contributing to a broader comprehension of the intricate connection between economic development and environmental sustainability. The study offers empirically supported findings about the effectiveness of energy efficiency strategies, the adoption of renewable energy sources, and the attraction of FDI in reducing CO2e. This pragmatic representation has the potential to influence policy-making approaches.

The remaining manuscript is presented in four sections: Section 2 delivers a relevant review of the literature for each study variable; Section 3 designates the theoretical framework and the methods used for empirical assessment; Section 4 tends to interpret and discuss the empirical results; and Section 5 concludes the argument along with the relevant policy implications.

2. Literature review

In this section, the contemporary study tends to review the existing and latest research regarding the association of various economic, financial, energy-related factors and CO2e.

2.1. Relations between GDP, FDI, and CO2e in the perspective of EKC curve

The literature concerning the titled variables' nexus is rich regarding the panel and time-series analysis. For instance, the current study of Leitão et al. (2023) examined the Visegrad nations during 1990–2018 and determined that the EKC paradox persists in the region. However, the FDI inflow strengthens the transformation of greener technologies and limits CO2e originated from energy consumption. Yet, Wang et al. (2023) asserted that income disparity transforms the EKC pattern from an inverted U-shape to N-shaped in panel examination. In case of the top nuclear energy economies, Jahanger et al. (2023) appealed the presence of the EKC paradox in the countries. Besides, the empirics revealed that improved ICT and nuclear energy significantly improve environmental quality in these economies. More recently, Sadiq et al. (2023) used GDP and GDP^2 as the key economic factors for identifying the EKC curve in the South Asian economies. The empirical results asserted that GDP positively while GDP^2 negatively affects the CO2e in these nations. In ASEAN economies, Pata et al. (2023) revealed that the elasticity of the long-run income is lesser than that of the short-run wealth.

Therefore, the EKC paradox is validated in these economies. Similarly, Manga et al. (2023) confirmed the existence of EKC curve for China and Thailand. On the contrary to above studies, the latest research indicates that FDI increases emissions, while trade and renewable energy use reduce it. Since economic expansion is the leading driver of environmental degradation (Jahanger and Usman 2023); the FDI and technological adoption significantly improves the region's environmental quality. From a time-series perspective, Kim and Seok (2023) and Udemba et al. (2020) analyses South Korea and China and conclude that initial growth improves pollution level, while the environmental degradation deteriorates when a threshold income level is achieved – hence, the EKC is valid. On the other hand, the FDI significantly contributes to pollution emissions in these countries. Nonetheless, Mahmood et al. (2020) validate the EKC paradox in North Africa, yet the role of FDI is insignificant in environmental quality assessment similar to Destek et al. (2023). On the other hand, Destek et al. (2023) argued that increasing FDI mitigate the environmental degradation in newly industrialized countries.

2.2. Relationships between renewable energy (re), energy efficiency (ENEF), and CO2e

In a time-series analysis for Sweden, Adebayo and Ullah (2023) use the wavelet approaches and conclude the presence of a negative correlation between ENEF, RE, and CO2e. Nonetheless, enhancement in the environmental degradation (i.e. CO2e) in the regions compels them to improve the production and adoption of RE and ENEF (Shah et al. 2023). In this regards, Qing et al. (2023) examine the correlation between the titled variables in BRICS economies by using the MMQR approach. The research concludes that GDP growth is the primary driver of emissions, whereas improved ENEF and RE significantly tackle the region's emissions issue. Using similar methods for China, Zhou et al. (2023) unveil that economic expansion is the key exploiter of environmental sustainability. However, China could reduce environmental degradation by increasing RE and ENEF as an emerging economy. Using the CS-ARDL approach, Wenlong et al. (2023) asserted that trading and institutional quality remain the key environmental degradation indicators. Still, the 10 Asian economies could achieve environmental sustainability by utilizing RE and improved ENEF. However, environmental policies and green finance are playing a key role in stemming the latter to eradicate negative environmental effects (Rasoulinezhad and Taghizadeh-Hesary 2022; Dzwigol et al. 2023). Although GDP growth, overpopulation, fossil fuel energy utilization, industrialization, and urbanization improved CO2e; still, the empirics revealed that RE and ENEF are significant tools for environmental recovery (see, e.g. Akram et al. 2020, 2022; Ponce and Khan 2021; Lei et al. 2022; Wang et al. 2022; Liguo et al. 2023; Destek et al. 2023; Tao et al. 2023).

2.3. Relationships between trade (TRD), technological innovation (TI), and CO2e

Concerning the impact of TRD on environment, the existing literature is quite rich yet contradictory. For instance, Gao et al. (2021) argued that foreign TRD substantially influences CO2e, yet the impact is different in various regions. Using the SC-ARDL methods, Wenlong et al. (2023) investigated Asian economies and asserted that TRD openness is adversely associated with CO2e, whereas TI improves the environment. In case of the two regions, i.e. BRICS and G7, Jiang and Liu (2023) claim that TRD openness improves waste in the BRICS economies while reducing it in the G7 economies. However, TI is favorable for environmental sustainability in both regions. Concerning the specific influence of TRD on consumption-based CO2e, Hassan et al. (2022) indicate that imports have a positive significant impact, while exports exhibit an adverse significant influence on the CO2e in RCEP countries during 1990–2020. Similar results are evident in the G7 economies (Wahab 2021). On the contrary to these estimations, the latest study of Liu et al. (2022) employed the FMOLS and DOLS approaches. It provides significant evidence on green international TRD and TI's adverse impact on environmental quality. Since most of the developing economies from the Belt and Road region have insufficient green development. Yet, foreign TRD and TI could enhance their development to a more green-oriented level (Xu et al. 2022). In the notion of OECD economies, Lu et al. (2022) claim that foreign TRD is unfavorable for environmental sustainability. Yet the institutional quality could transform the positive impact into negative. Since the TRD is a significant driver of economic expansion, it significantly and positively impacts CO2e. Therefore, the TRD and TI have a causal impact on the CO2e.

2.4. Literature summary and research gap

After studying the literature, this study observed that the existing studies generally contradict the empirical indication concerning the relationship of various economic and non-economic variables. To be more specific, this study observed the mixed influence of TRD, FDI, and TI. However, the influence of other variables, such as GDP and RE may be attributed as positive in all the cases. Besides, earlier research has used traditional econometric approaches, which could lead to biased estimates. Moreover, the present research noted that empirical evidence is more concentrated on analyzing developed and developing economies while leaving room and gaps for emerging economies like BRICS economies. As a result, contemporary research tends to bridge the gap by analyzing the key indicators of environmental quality to formulate relevant policies and attain sustainable development in the region. Unlike the existing literature, this research uses advanced diagnostic (cross-sectional dependence and slope heterogeneity) tests, cointegration tests, and second-generation long-run estimators.

3. Methodology

3.1. Theoretical framework

The theoretical notion through which various economic, financial, and technological variables affect CO2e in the BRICS is provided in this section.

The notion of the EKC suggests an irregular connection exists between the level of economic growth and the extent of environmental deterioration (Gu et al. 2023). The early phase of economic expansion is accompanied by a rise in CO2e due to industrialization in the BRICS nations (Baloch et al. 2019). Once a society or nation reaches a certain level of affluence, there is a noticeable increase in the significance placed on environmental issues. This heightened awareness leads to implementing policies and developing green technologies to address these concerns. Consequently, there is a subsequent reduction in the CO2e produced per unit of GDP (Van Alstine and Neumayer 2010). The BRICS countries, such as China and India, exemplify this trend by showing indications of migrating towards more environmentally friendly businesses as their economic levels increase. The EKC framework posits that as economies progress, they have the potential to curtail emissions via the adoption of sustainable practices and green policies (Xia et al. 2022).

TRD can potentially impact CO2e inside the BRICS economies via numerous channels. The phenomenon of foreign trade has the potential to facilitate the relocation of energy-intensive sectors to certain countries, possibly resulting in an escalation of emissions. On the other hand, it is worth noting that trade can facilitate the dissemination of more environmentally friendly technology and practices, hence reducing emissions (Duval 2008). The overall outcome is contingent upon the equilibrium between sectors with high emissions and those more environmentally friendly in the context of trade. FDI has the potential to influence carbon emissions in several ways. According to Elliott et al. (2013), there is a possibility that the presence of energy-intensive enterprises might increase emissions. Nevertheless, FDI has the potential to enable the transfer of environmentally friendly technology and efficient management practices, hence decreasing emissions (Yi et al. 2022). The total influence is contingent upon the specific sectors in which FDI is allocated and the environmental regulations the host nation implements.

TI has a crucial role in mitigating carbon emissions. According to Shahzad et al. (2021), Ahmad and Zheng (2021), and You et al. (2023), the introduction of innovations has the potential to facilitate the development of technologies that are characterized by enhanced cleanliness and energy efficiency. Concurrently, adopting energy-intensive manufacturing methods resulting from significant technical breakthroughs may lead to increased emissions (Janipour et al. 2020). The overall outcome is contingent upon the equilibrium between innovations aimed at lowering emissions and those that are emission-intensive. Renewable energy sources, sometimes referred to as green energy, have the capacity to substantially mitigate carbon emissions. The heightened embracing of renewable's sources has the potential to significantly diminish emissions due to their capacity to serve as a cleaner fossil fuels' substitute (Qin et al. 2021a, 2021b; Cai et al. 2022). The connection between green energy use and the decrease in emissions is unmistakable and in line with the sustainability objectives. In case of the BRICS economies, the expected outcomes are portrayed in Figure 3

3.2. Models construction

Subsequent to the research work of Tariq et al. (2022), this study constructed the following model:

Model 1

$$CO_{2e,it} = \alpha_1 + \alpha_2 GDP_{it} + \alpha_3 GDPS_{it} + \alpha_4 ENEF_{it} + \alpha_5 RELOT_{it} + \varepsilon_{it} \tag{1}$$

In the above research model, it can be observed that GDP, ENEF, and RELOT are the factors of CO2e. Where the squared GDP (GDPS) is included in the model for evaluating the EKC hypothesis. Additionally to GDP, GDPS, and ENEF, this research considers the role of FDI, TI, and TRD, on CO2e, which is provided in the extended form as Model 2:

Model 2

$$CO_{2e,it} = \alpha_1 + \alpha_2 GDP_{it} + \alpha_3 GDPS_{it} + \alpha_4 FDI_{it} + \alpha_5 TI_{it} + \alpha_6 TRD_{it} + \alpha_7 ENEF_{it} + \varepsilon_{it} \tag{2}$$

Further, this research examines the greener energies influence on CO2e in emerging countries. Regard, the present research considers energy related variables, including RECN, ENEF, and RELOT, along with the GDP and GDPS for EKC examination and the regression form is provided as Model 3:

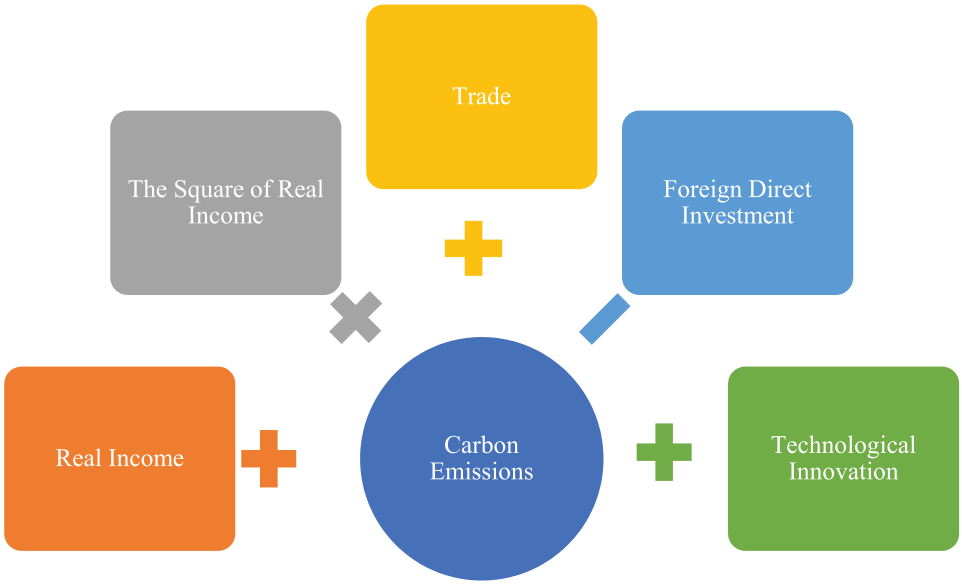

Figure 3. Summary of empirical findings.

Model 3

$$CO_{2e,it} = \alpha_1 + \alpha_2 GDP_{it} + \alpha_3 GDPS_{it} + \alpha_4 RECN_{it} + \alpha_5 ENEF_{it} + \alpha_6 RELOT_{it} + \varepsilon_{it} \quad (3)$$

In the above models, it must be noted that α_1 is the intercept of all models, whereas $\alpha_{2,3,\ldots,7}$ are the slopes for each regressor. In addition, ε represents the standard error of the models. In contrast, the cross-sections and time-series are represented via i and t, respectively, covering the period from 1990–2022 for the BRICS (Brazil, Russia, India, China, and South Africa) economies. The consideration of BRICS economies in this academic framework is of utmost importance owing to their significant global economic impact. These entities embody a wide range of socioeconomic situations, and their growth paths have implications for other sectors, such as trade, energy, technology, and the environment. Examining these countries yields great insights into intricate processes and contributes to formulating global policies promoting sustainable development. The specifications and units of each variable are presented in Table 1.

The methodology used in this research is purely based on the panel data analysis, where the methodological flow can be observed graphically in Figure 4.

3.3. Analytical approach

The preliminary phases of this investigation include doing a descriptive evaluation and performing normalcy tests on all components. This study calculates the mean, median, and range (highest and lowest) of the data series collected from the panel. The calculated standard deviation demonstrates the variability in the information across time due to variations in the range of values. Moreover, the use of skewness as well as Kurtosis evaluates the normalcy of the data. Similarly, the normalcy evaluation proposed by Jarque and Bera (1987) was utilized, which considers the excess kurtosis and skewness while maintaining zero values for both. Jarque and Bera (1987) used a statistical methodology to assess the normality of the data given below:

$$JB = \frac{N}{6}\left(S^2 + \frac{(K-3)^2}{4}\right) \quad (4)$$

In addition, this work employs two diagnostic procedures to identify heterogeneity in the slope coefficient (SCH) and cross-section dependency (CD). In the contemporary period of advancement, nations exchange diverse goods and services due to their specialization in certain commodities or services. Consequently, a nation may rely on another geographical area to achieve its growth objectives. Moreover, the nation can implement policies resembling those of other countries, perhaps resulting in a slope homogeneity. Disregarding these concerns may produce potentially deceptive and partial outcomes (Wei et al. 2022).

Table 1. Variables specifications and data sources.

Variable	Specification	Data Source
CO2e	Emissions of carbon dioxide measured in kt	World Bank (2023)
GDP	Gross domestic product measured as constant US$ 2015	
FDI	Foreign direct investment net inflow % OF GDP	
ENEF	GDP per unit of energy consumption (constant 2017 PPP $ per KG of oil equivalent.	
RELOT	Renewable electricity output (% of total electricity output)	
RECN	Renewable energy consumption (% of total final energy utilization)	
TI	Patents registered by residents and non-residents	
TRD	Trade (% of GDP)	

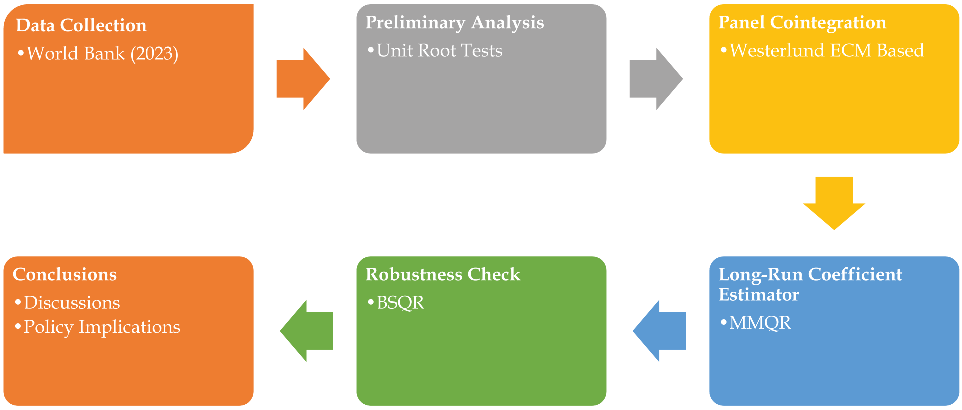

Figure 4. Methodological flow.

Hence, the current research used the Pesaran and Yamagata (2008) SCH methodology, which includes both the SCH and adjusted SCH (ASCH) formulations as shown below:

$$\hat{\Delta}_{SCH} = \sqrt{N(2k)^{-1}}\left(N^{-1}S' - K\right) \tag{5}$$

$$\hat{\Delta}_{ASCH} = \sqrt{N}\sqrt{\frac{T+1}{2K.(T-K-1)}}\left(N^{-1}S' - 2K\right) \tag{6}$$

Based on the null hypothesis (H0), the slopes exhibit homogeneity.

In contrast, this research utilizes the Pesaran (2004) CD test to evaluate the earlier mentioned concerns. The specific test and the H_0 of no cross-sectional dependence is shown below.

$$CD_{Test} = \frac{\sqrt{2T}}{[N(N-1)]^{1/2}}\sum_{i=1}^{N-1}\sum_{k=1+i}^{N} T_{ik} \tag{7}$$

To get accurate long-run coefficients, it is necessary to assess the stationarity of the factors. The present research utilizes the second-generation CIPS stationarity estimator – pioneered by Pesaran (2007), by expanding upon the factor modeling technique introduced by Pesaran (2006). In contrast to other unit root tests, this technique effectively addresses the concerns associated with the SCH and the CD.

The current work utilizes the error correction (EC) context created by Westlund (2007) to analyze the long-term equilibrium of the parameters. The underlying assumption of this evaluation is that the EC term is assumed to have a zero value. To tackle the issues of SCH and CD, this test provides reliable estimations by including both the mean group $\left[G_\tau = \frac{1}{N}\sum_{i=1}^{N}\frac{\hat{a}_i}{S.E\hat{a}_i}; G_a = \frac{1}{N}\sum_{i=1}^{N}\frac{T\hat{a}_i}{\hat{a}_i(1)}\right]$ and panel statistics $\left[P_\tau = \frac{\hat{a}}{S.E(\widehat{a})}; P_a = T.\hat{a}\right]$.

Advanced methodologies may be used to develop persistent predictions for precise predictions. Consequently, the current research employs the Method of Moment Quantile Regression (MMQR) estimate approach proposed by Destek and Sarkodie (2019). The superiority of this technique over simple regression models stems from its ability to assess coefficients at a specific region and scale. This methodology is precise than other methods since it considers the impacts of individual quantiles instead of the mean influence. Moreover, given its ability to address the endogeneity problem, this methodology is appropriate for conducting long-term correlation investigation. The equation representing the location-scale variance $Q_y(\tau|R)$ is described with the following implications:

$$Y_{it} = \alpha_i + \beta R_{it} + \left(\gamma_i + \rho Z'_{it}\right)\mu_{it}, \tag{8}$$

The above equation incorporates a probabilistic formula, where the probability of $p\left(\gamma_i + \rho Z'_{it} > 0\right)$ is equal to 1. In the present inquiry, the parameters α, β, γ, and ρ are used to determine the expected values. The subscript i denotes a fixed impact in this particular case, as seen by the constrained. α_i and γ_i (where $i = 1, 2, \ldots, n$). The k-vector, denoted as Z, and the vector '$\daleth$', on the contrary, illustrate the fluctuations of R.

$$Z_{\mathbb{I}} = Z_{\daleth}(R), \daleth = 1, 2, \ldots, k, \tag{9}$$

In the equation mentioned earlier, the parameter R_{it} is allocated symmetrically and autonomously over both time *(t)* and *i*. This allocation is consistent and orthogonal to both *i* and *t* while also sustaining the integrity of the external observations and reserves (Machado and Silva 2019). Based on the rationale mentioned above, the research models [Eq. (1), (2), and (3)] used in this investigation may be generally reformulated as follows:

$$Q_y(\tau|R_{it}) = (\alpha_i + \gamma_i q(\tau)) + \beta R_{it} + \rho Z'_{it} q(\tau), \tag{10}$$

In this study, the variable R_{it} Represents the explanatory factors, namely $GDP, GDPS, ENEF, RELOT, FDI, TI, TRD, and RECN$. Once transformed into the natural logarithm, all components are shown as percentages. In addition to this,

Table 2. Descriptive statistics and normality estimates.

	CO2e	FDI	GDP	ENEF	RELOT	RECN	TI	TRD
Mean	2051132	2.031	2.16E+12	6.182	27.814	24.846	117397.1	40.933
Median	1215205	1.753	1.23E+12	5.209	17.261	18.570	24863.67	42.199
Maximum	10944686	9.856	1.63E+13	11.319	95.405	52.950	1542002	110.577
Minimum	197897.4	−1.925	1.79E+11	1.857	0.084	3.180	3140.000	15.156
Std. Dev.	2717835	1.606	3.15E+12	2.672	29.654	17.378	316247.5	14.736
Skewness	2.173	1.032	2.917	0.787	1.345	0.155	3.556	0.504
Kurtosis	6.720	5.352	11.093	2.323	3.243	1.421	14.521	4.583
Jarque-Bera	225.064	67.291	684.164	20.202	50.183	17.812	1260.127	24.230
Probability	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

R_{it} provides insight into the dispersion of the coefficients of regression, as shown by the variable Y_{it}, which represents CO_{2e} and is also influenced by quantiles. Furthermore, the expression $-\alpha_i(\tau)\equiv\alpha_i+\gamma_i q(\tau)$ indicates the vector element that consistently influences i but does not have any effect on the intercept values. Finally, $q(\tau)$ denotes the $\tau-th$ quantile sample, namely Q0.25, Q0.50, Q0.75, and Q0.90. The quantile formulation used in the present examination is as follows:

$$min_q \sum_i \sum_t \theta_\tau \left(R_{it} - \left(\gamma_i + \rho Z'_{it}\right) q\right) \tag{11}$$

The evaluation method, denoted as $\theta_\tau(A)$, may be expressed as follows: $\theta_\tau(A) = (\tau - 1)AI\{A \leq 0\} + TAI\{A > 0\}$.

Based on the results of the MMQR approach, this study employs a non-parametric technique, namely the bootstrap quantile regression (BSQR), to assess the robustness of the model. The latter approach offers empirical estimates at each particular quantile, making it an essential technique due to its ability to handle the problem of non-normality in the information. Upon obtaining the coefficients, this research examined the causal linkage between the factors under examination. The current work used the Pairwise Dumitrescu and Hurlin (2012) Panel causality test to address the concerns related to the SCH, CD, and panel imbalance (N>T or T>N).

4. Results and discussion

This section offers the estimated predictions, their interpretations and the respective discussion from the economic rationale perspective.

4.1. Results interpretation

This research originated the empirical estimations by evaluating the statistical outcomes of descriptive information for the selected variables, as presented in Table 2. The outcomes asserted that the mean and median for all the variables are slightly different. The range values specify the difference between the minimum and the maximum of observations in the panel information, which further leads to evaluating the standard deviation for each selected variable. In the latter evaluation, GDP is a highly fluctuating variable, followed by CO2e, TI, and RELOT. Concerning the normality distribution, this study indicates that the skewness and Kurtosis for all variables hold different statistical values than their respective critical values. Also, the non-normality issue is evident in the inclusive assessment of Jarque and Bera (1987).

Table 3. The results of cross-sectional dependency test.

Variable	CD-test
CO_{2e}	7.39***
GDP	16.716***
GDPS	16.733***
FDI	7.047***
TI	10.528***
TRD	7.527***
RECN	10.05***
RELOT	−2.4**
ENEF	6.727***

Note: For significance level,***=1%**= 5% and *= 10%

Once the normality and descriptive analysis are attained, this study uses two diagnostic tests before panel data investigation. The estimates for CD assessments are presented in Table 3. The predicted estimates asserted that the study variables hold significant values at 1% and 5% levels, leading to the negligence of H_0 and concluding the occurrence of cross-section dependence in the panel variables. Such results validate that any changes in a variable in one BRICS economy may have a spillover effect on the variables in other BRICS regions.

After attaining the CD results, this research analyzes the slope heterogeneity, possibly caused by implementing identical policies across BRICS regions. The estimated outcomes for the three models are presented in Table 4, which elucidates significant results at a 1% level. Such significant estimates discard H_0 and accomplish that the slopes are heterogeneous for the variables in the BRICS economies. This further strengthened the adoption of panel approaches for testing the stationarity and cointegration.

Table 4. The results of slope homogeneity test.

Tests	Model 1	Model 2	Model 3
ACH	11.773***	6.676***	16.108***
SCH_{Adj}	13.015***	7.670***	18.147***

Note: For significance level,***=1%**= 5% and *= 10%

Table 5. The results of stationarity test.

Pesaran (2007) CIPS		
Variable	I(0)	I(1)
CO_{2e}	−1.945	−4.056***
GDP	−2.451	−3.518***
GDPS	−2.370	−3.480***
FDI	−2.999**	—
TI	−2.602	−5.008***
TRD	−2.984**	—
RECN	−2.333	−4.290***
RELOT	−2.306	−5.856***
ENEF	−3.028**	—

Note: For significance level,***=1%**= 5% and *= 10%

After diagnostic assessments, this work analyzes the stationarity properties of the examined variables. The present study uses the Pesaran (2007) CIPS estimator, and the predicted estimates are reported in Table 5. The outcomes asserted that the statistical values of only three variables (FDI, TRD, and ENEF) are significant at 5%, while other variables are insignificant at I(0). However, after testing the stationarity properties of these factors at I(1), this research noted that all the remaining variables (CO2e, GDP, GDPS, TI, RECN, and RELOT) reject the null hypothesis at 1% levels and concludes the unit root's absence in the BRICS' panel variables. The stationarity of these variables leads the present study to examine the cointegration among the variables specified empirically.

To test the long-run connection between considered variables, the current study uses the Westerlund (2007) ECM approach and the predicted results are provided in Table 6. From the predicted estimations, the present work detected that the cointegration between the variables in all three models exists. Since the statistical values of panel and group statistics are statistically substantial at 1% levels in the designated models. Consequently, this research rejects H_0 of no cointegration between the factors and accomplishes the validity of long-run equilibrium linkage between the variables.

After confirming the stationarity and symmetrical long-run association, this research tends to analyze the precise influence of each regressor on CO2e. The predicted outcomes of Model 1 are presented in Table 7. The MMQR results asserted that economic growth measured as GDP significantly improves CO2e in BRICS nations. However, reaching the income to a threshold level, the influence of a higher income level measured as GDPS adversely influences CO2e. The estimated outcomes of this study are not unique. Instead, the results are similar to the empirical work (Udemba et al. 2020; Jahanger and Usman 2023; Kim and Seok 2023; Destek et al. 2023), confirming the EKC hypothesis in different regions. On the contrary, the influence of ENEF and RELOT is found to be significant and negative on the CO2e, which indicates that a percentage enhancement in each of these variables leads to a reduction in the emissions level by 1.187—1.299 and 0.266—0.241% across the quantiles. Such results are similar to the empirical findings of Shah et al. (2023), Qing et al. (2023), and Zhou et al. (2023), confirming the progressive role of these variables in environmental sustainability.

Once the primary study model is analyzed, this study also evaluated Model 2 via MMQR and the predicted results are presented in Table 8. From the outcomes, this research observed the positive and negative impact of GDP and GDPS, validating the EKC paradox in the BRICS nations. Besides, the impact of TI (significant in the first quantile) and TRD (significant in the last three quantiles) is positive, indicating that enhancing trading activities and technologies could encourage industrial production

Table 6. The results of panel cointegration analysis.

	Model 1		Model 2		Model 3	
Statistic	Val.	Z-val.	Val.	Z-val.	Val.	Z-val.
G_t	−7.872***	−12.813	−7.504***	−11.129	−8.180***	−13.146
G_a	−15.865**	−1.882	−13.930	−0.019	−14.401	−0.780
P_t	−17.623***	−11.057	−17.467***	−10.653	−16.917***	−10.400
P_a	−17.378***	−3.445	−14.514	−1.151	−15.932**	−2.221

Note: For significance level,***=1%**= 5% and *= 10%

Table 7. The results of MMQR procedure [baseline model (Model 1)].

Var.	Loc.	Scal.	Quantiles			
			$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$	$Q_{0.90}$
GDP	9.225***	1.581***	7.750***	9.307***	10.717***	11.710***
	[0.990]	[0.548]	[1.177]	[1.016]	[1.050]	[1.197]
GDPS	−0.333***	−0.065***	−0.272***	−0.336***	−0.394***	−0.435***
	[0.040]	[0.022]	[0.047]	[0.041]	[0.042]	[0.048]
ENEF	−1.229***	−0.045	−1.187***	−1.231***	−1.271***	−1.299***
	[0.067]	[0.037]	[0.080]	[0.067]	[0.071]	[0.081]
RELOT	−0.257***	0.010	−0.266***	−0.257***	−0.248***	−0.241***
	[0.029]	[0.016]	[0.034]	[0.029]	[0.030]	[0.035]
CONS.	−55.567***	−9.445***	−46.749***	−56.052***	−64.479***	−70.414***
	[6.138]	[3.400]	[7.297]	[6.285]	[6.508]	[7.425]

Note: For significance level,***=1%**= 5% and *= 10%

Table 8. The results of MMQR procedure [Model 2].

Var.	Loc.	Scal.	Quantiles			
			$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$	$Q_{0.90}$
GDP	3.364***	1.205**	2.321***	3.091***	4.435***	5.472***
	[0.857]	[0.583]	[0.744]	[0.809]	[1.215]	[1.630]
GDPS	−0.100***	−0.042	−0.064*	−0.091**	−0.137**	−0.173**
	[0.038]	[0.026]	[0.033]	[0.036]	[0.054]	[0.073]
FDI	−0.092***	−0.068***	−0.033	−0.076***	−0.152***	−0.210***
	[0.029]	[0.020]	[0.025]	[0.028]	[0.042]	[0.053]
TI	0.022	−0.130**	0.135**	0.052	−0.094	−0.206
	[0.078]	[0.053]	[0.067]	[0.074]	[0.111]	[0.146]
TRD	0.537***	0.142**	0.414***	0.505***	0.663***	0.785***
	[0.098]	[0.067]	[0.085]	[0.093]	[0.139]	[0.185]
ENEF	−1.236***	0.114***	−1.335***	−1.262***	−1.134***	−1.036***
	[0.059]	[0.040]	[0.051]	[0.057]	[0.084]	[0.110]
CONS.	−19.946***	−8.119**	−12.921***	−18.107***	−27.167***	−34.157***
	[5.002]	[3.405]	[4.338]	[4.746]	[7.107]	[9.500]

Note: For significance level,***=1%**= 5% and *= 10%

and carbon-intensive fossil fuel consumption. Consequently, the environmental challenges may be enhanced in the BRICS region. Such outcomes are also offered by the recent studies of Hassan et al. (2022) and Liu et al. (2022). On the other hand, FDI and ENEF are observed to exhibit a substantial adverse impact on the CO2e in the region. More precisely, a percentage enhancement in both the latter variables substantially reduces CO2e by 0.076—0.210 and 1.335—1.036%, which is significant (1% level). These predictions designate that FDI and ENEF are the key instruments for BRICS environmental sustainability, which are identical to the studies of Leitão et al. (2023), Wenlong et al. (2023), and Akram et al. (2022).

With reference to Model 3, the predicted estimates of MMQR are portrayed in Table 9. From the examined estimates, it can be noted that the EKC paradox persists in BRICS regions. Such results, i.e. a positive noteworthy impact of GDP and a harmful significant influence of GDPS, further strengthen the EKC paradox statement in the selected economies. The existence of the EKC in other regions is also validated by different scholars like Wang et al. (2023), Jahanger et al. (2023) and Sadiq et al. (2023). On the contrary, the under-discussion model incorporates three environmentally friendly energy indicators, i.e. RECN, ENEF, and RELOT. The estimation outcomes indicate that all three variables have a negative significance in the CO2e, which is vastly significant at 1, 5, and 10% levels. In particular, a percentage augmentation in each of these factors substantially diminishes the CO2e levels by 0.156—0.169 (RECN), 1.072—1.385 (ENEF), and 0.225—0.293 (RELOT) percent. The outcomes asserted that renewable energy output, consumption, and energy efficiency are yet to be strengthened in these emerging economies. Still, their influence is strong enough to enhance environmental sustainability. These assessments are similar to the empirical literature (Lei et al. 2022; Wang et al. 2022).

Once the study models are estimated, the current work tends to assess the authenticity of the models discussed earlier. This research uses the BSQR method, and the predicted estimations are reported in Table 10 for all the models. From the examined outcomes, this research noted that the EKC hypothesis persists in the BRICS economies, as depicted by the progressive influence of GDP and the adverse influence of GDPS on CO2e in all the models. The validity of EKC strengthens the empirics obtained via MMQR, and is also similar to the findings of Sadiq et al. (2023) and Mahmood et al. (2020). Besides, the results underscore the positive influence of TI and TRD on CO2e. Although the influence is not strong, it is significant only in one and two quantiles. These estimations are also in line with the

Table 9. The results of MMQR procedure [Model 3].

Var.	Loc.	Scal.	Quantiles			
			$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$	$Q_{0.90}$
GDP	8.924***	2.466**	6.815***	7.857***	11.833***	13.283***
	[1.487]	[1.082]	[0.917]	[1.277]	[2.526]	[3.112]
GDPS	−0.321***	−0.101**	−0.234***	−0.277***	−0.440***	−0.499***
	[0.060]	[0.043]	[0.037]	[0.051]	[0.101]	[0.124]
RECN	−0.050	0.124***	−0.156***	−0.104**	−0.096*	−0.169**
	[0.038]	[0.028]	[0.021]	[0.040]	[0.058]	[0.071]
ENEF	−1.174***	−0.119	−1.072***	−1.122***	−1.315***	−1.385***
	[0.124]	[0.091]	[0.078]	[0.101]	[0.215]	[0.265]
RELOT	−0.247***	−0.026	−0.225***	−0.236***	−0.278***	−0.293***
	[0.041]	[0.030]	[0.026]	[0.032]	[0.071]	[0.088]
CONS.	−53.688***	−14.985**	−40.870***	−47.203***	−71.371***	−80.180***
	[9.236]	[6.723]	[5.707]	[7.900]	[15.711]	[19.356]

Note: For significance level,***=1%**= 5% and *= 10%

Table 10. Robustness checks – BSQR.

Variable	Quantiles [Baseline Model (Model 1)]			
	$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$	$Q_{0.90}$
GDP	5.575***	8.340***	6.911***	7.846***
GDPS	−0.183***	−0.298***	−0.244***	−0.280***
ENEF	−1.141***	−1.580***	−0.978***	−0.950***
RELOT	−0.245***	−0.205***	−0.069	−0.098***
CONS.	−33.520***	−49.821***	−40.908***	−46.805***
Model 2				
GDP	2.069**	2.830***	4.749***	5.223***
GDPS	−0.054	−0.085**	−0.161***	−0.181***
FDI	−0.021	−0.020	−0.064	−0.046**
TI	0.126	0.137**	0.087	−0.089
TRD	0.451***	0.536***	0.172	0.130
ENEF	−1.282***	−1.226***	−0.717***	−0.690***
CONS.	−11.452**	−16.271***	−27.789***	−30.619***
Model 3				
GDP	3.443***	3.733***	13.923***	12.127***
GDPS	−0.099**	−0.111**	−0.522***	−0.451***
RECN	−0.180***	−0.163***	−177.000**	−0.159***
ENEF	−1.215***	−1.287***	−1.821***	−1.542***
RELOT	−0.135***	−0.126***	−0.298**	−0.233***
CONS.	−19.880**	−21.502***	−84.286***	−73.167***

Note: For significance level,***=1%**= 5% and *= 10%

empirics obtained via MMQR. In contrast, ENEF, RELOT, FDI, and RECN influence is found negative and statistically significant at 1, 5, and 10% levels. Such substantial estimates validate and authenticate the empirical results of the earlier estimator. Although each variable's magnitude is relatively different, the route of the impact is similar (negative), which is consistent with the empirical work of Pata et al. (2023), Ponce and Khan (2021), and Akram et al. (2020).

Once the robustness of the models is tested, the present study observed the lack of causality analysis in the MMQR and BSQR approaches. In this response, the present research uses the pairwise Granger causality estimator and the predicted outcomes are portrayed in Table 11. From the approximations, the present research observed a bidirectional causal connection of regressors with CO2e except for the RECN → CO_{2e}, where there is one-way causality from RECN to CO2e. On the other hand, the bidirectional causal nexus indicates that income, FDI, ENEF, RELOT, TI, and TRD could be substantial policy tools for environmental sustainability in these emerging economies.

Table 11. The results of panel causality test.

H_0:	W-Stat.	Zbar-Stat.	Prob.
Panel Causality Test			
GDP → CO_{2e}	4.53314**	3.34791	0.0279
CO_{2e} → GDP	9.98159***	7.41895	1.E−13
GDPS → CO_{2e}	5.46689**	4.28501	0.0156
CO_{2e} → GDPS	10.0953***	7.52690	5.E−14
FDI → CO_{2e}	6.66058***	5.48045	0.0009
CO_{2e} → FDI	7.76431***	5.31401	1.E−07
ENEF → CO_{2e}	4.99020***	2.68047	0.0074
CO_{2e} → ENEF	4.91450***	2.60861	0.0091
RECN → CO_{2e}	4.70716**	2.41177	0.0159
CO_{2e} → RECN	2.91982	0.71499	0.4746
RELOT → CO_{2e}	4.99505***	2.68507	0.0073
CO_{2e} → RELOT	6.59987***	4.20858	3.E−05
TI → CO_{2e}	4.09408**	1.82975	0.0673
CO_{2e} → TI	4.57433**	2.28566	0.0223
TRD → CO_{2e}	7.23221***	4.80888	2.E−06
CO_{2e} → TRD	4.18745*	1.91840	0.0551

Note: For significance level,***=1%**= 5% and *= 10%

4.2. Discussion

The interactions of economic expansion, environmental factors, and CO2e have received considerable scholarly and public interest in recent years, with a special focus on the BRICS economies. The discussion below presents the economic justification for these associations, drawing upon empirical evidence. The presence of an encouraging and substantial correlation between GDP and CO2e in BRICS countries has been validated in this work, as shown in previous studies (Sadiq et al. 2023). As these countries undergo a period of accelerated economic growth, there is an increased need for energy and industrial operations, typically dependent on the use of fossil fuels (Mahmood et al. 2020). Consequently, this phenomenon leads to a rise in CO2e. This tendency is consistent with the EKC theory, which posits that environmental deterioration tends to deteriorate in the early stages of GDP expansion but improves when a particular income level is surpassed (Leitão et al. 2023). Furthermore, the adverse and statistically significant influence of GDPS on CO2e supports an inverted U-shaped EKC pattern within these economies (Sadiq et al. 2023). In the initial stages, the expansion of the economy amplifies CO2e. However, as income levels continue to increase, there is a tendency for environmental concerns and laws to become more prominent. Consequently, this leads to a decline in emissions to the pace of economic development. In addition, it has been shown that there is a notable positive correlation between CO2e and TI and foreign trade in these economies (Wahab 2021; Liu et al. 2022). Advanced technologies often need elevated energy consumption, but international commerce might result in the migration of energy-intensive companies to these nations. This highlights the need to tackle the environmental repercussions associated with technological advancements and the promotion of free trade.

In contrast, the observed adverse and statistically significant impact of ENEF, FDI, RECN, and RELOT on CO2e may be seen as indicative of the proactive measures undertaken by BRICS countries to reduce their environmental impact (Akram et al. 2020; Ponce and Khan 2021). Developments in renewable energy sources, energy efficiency, and cleaner technology are paramount in mitigating CO2e. Furthermore, FDI has the potential to support the implementation of more environmentally friendly industrial practices and technology. Moreover, the bidirectional causal relationship between these explanatory factors and CO2e is of significant importance, as it underscores the complex dynamics of the problem (Leitão et al. 2023). Although economic expansion often results in heightened emissions, it may also stimulate investments in cleaner technology and enhance energy efficiency. Similarly, technological improvements have the potential to both augment and diminish emissions concurrently. Therefore, the economic justification for the correlation between these factors and CO2e in BRICS countries is complex. Although there is a correlation between economic expansion and increasing emissions, an EKC implies the possibility of environmental improvement with ongoing development. Policymakers must prioritize promoting sustainable development, encouraging clean technology implementation, and using renewable energy sources to address and alleviate the environmental consequences associated with economic progress in these countries.

5. Concluding remarks

5.1. Conclusion

This research attempted a comprehensive examination of the correlation between economic development, FDI, TI, trade, ENEF, and CO2e in the economies of the BRICS region spanning 1990 to 2022. The present study enhances the existing body of literature by validating the existence of the EKC hypothesis among the BRICS states. Our observation indicates a positive correlation between economic expansion and the rise in CO2e. Nevertheless, once these nations reach a certain level of affluence, the focus shifts towards environmental sustainability, leading to a reduction in emissions relative to GDP. This highlights the significance of ongoing economic growth in conjunction with environmental initiatives. Moreover, the research underscored the favorable influence of technological advancement and foreign trade on CO2e, indicating the need for policies promoting cleaner technology and sustainable trade methodologies. Our study findings highlight the crucial impact of ENEF, renewable energy consumption, renewable electricity generation, and FDI in mitigating CO2e, fostering the preservation of the environment, and facilitating the shift towards sustainable energy sources. The intricate link between these characteristics and CO2e highlights the bidirectional causality connection, underscoring the need for extensive and coordinated approaches to attain sustainable development in BRICS nations.

5.2. Policy implications

The results of this research have significant policy implications for the BRICS nations as they strive for sustainable growth via green energy. Policymakers need to acknowledge the initial beneficial connection between economic expansion and emissions. As the BRICS nations reach the critical juncture of the EKC, they must give precedence to sustainability initiatives. These initiatives should include the implementation of rigorous environmental legislation and the provision of subsidies to foster green innovation. Although evidence suggests that technology innovation significantly contributes to pollution emissions, it is important to acknowledge that it can also provide sustainable solutions. Policymakers must provide incentives for advancing research and development in environmentally friendly technologies while offering substantial assistance for their integration within various sectors. Further, trade policies must be congruent with environmental goals. Promoting the widespread use of cleaner technology in producing traded products may effectively contribute to reducing emissions associated with global trade. Significant reduction in carbon emissions may be achieved by prioritizing energy efficiency, renewable energy consumption, clean electricity generation, and attracting FDI in green technology. Governments must provide incentives and establish aggressive objectives for adopting renewable energy sources. Moreover, it is essential for authorities to proactively pursue FDI per objectives related to environmentally friendly and sustainable development. This can enhance the dissemination of ecologically sustainable technology and practices.

5.3. Limitations and future research directions

This research recognizes several limitations. The primary emphasis of the analysis centers on a particular time span ranging from 1990 to 2022, which may inadvertently neglect broader and more enduring patterns and transformations. Subsequent investigations should consider expanding the study to include the progressive dynamics occurring over a more extended duration. In addition, examining the heterogeneity within the BRICS states and considering the influence of regional variances in policies and results would contribute to a more comprehensive and nuanced understanding. Furthermore, one area of study that has potential for future investigation is evaluating the effectiveness of certain policy measures designed to facilitate green energy adoption and promote environmental sustainability. A thorough analysis of the socioeconomic aspects associated with adopting renewable energy sources in the BRICS economies might provide a holistic comprehension of the trajectory towards achieving sustainable development.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Adebayo TS, Ullah S. 2023. Towards a sustainable future: the role of energy efficiency, renewable energy, and urbanization in limiting CO2 emissions in Sweden. Sustain Dev. doi: 10.1002/sd.2658.

Ahmad M, Zheng J. 2021. Do innovation in environmental-related technologies cyclically and asymmetrically affect environmental sustainability in BRICS nations? Technol Soc. 67:101746. doi: 10.1016/j.techsoc.2021.101746.

Akram R, Chen F, Khalid F, Ye Z, MT M. 2020. Heterogeneous effects of energy efficiency and renewable energy on carbon emissions: evidence from developing countries. J Clean Prod. 247:119122. doi: 10.1016/j.jclepro.2019.119122.

Akram R, Umar M, Xiaoli G, Chen F. 2022. Dynamic linkages between energy efficiency, renewable energy along with economic growth and carbon emission. A case of MINT countries an asymmetric analysis. Ener Rep. 8:2119–2130. doi: 10.1016/j.egyr.2022.01.153.

Ali A, Radulescu M, Lorente DB, Hoang VNV. 2022. An analysis of the impact of clean and non-clean energy consumption on economic growth and carbon emission: evidence from PIMC countries. Environ Sci Pollut R. 29(34):51442–51455. doi: 10.1016/j.egyr.2022.01.153.

Bakhsh K, Rose S, Ali MF, Ahmad N, Shahbaz M. 2017. Economic growth, CO2 emissions, renewable waste and FDI relation in Pakistan: new evidences from 3SLS. J Environ Manage. 196:627–632. doi: 10.1016/j.jenvman.2017.03.029.

Baloch MA, Mahmood N, Zhang JW, Zhang JW. 2019. Effect of natural resources, renewable energy and economic development on CO2 emissions in BRICS countries. Sci Total Environ. 678:632–638. doi: 10.1016/j.scitotenv.2019.05.028.

Balsalobre-Lorente D, Ibáñez-Luzón L, Usman M, Shahbaz M. 2022. The environmental Kuznets curve, based on the economic complexity, and the pollution haven hypothesis in PIIGS countries. Renew Energ. 185:1441–1455. doi: 10.1016/j.renene.2021.10.059.

Bashir MA, Dengfeng Z, Bashir MF, Rahim S, Xi Z. 2023. Exploring the role of economic and institutional indicators for carbon and GHG emissions: policy-based analysis for OECD countries. Environ Sci Pollut R. 30(12):32722–32736. doi: 10.1007/s11356-022-24332-7.

Cai X, Wang W, Rao A, Rahim S, Zhao X. 2022. Regional sustainable development and spatial effects from the perspective of renewable energy. Front Environ Sci. 10:166. doi: 10.3389/fenvs.2022.859523.

Destek MA, Hossain MR, Khan Z. 2023. Premature deindustrialization and environmental degradation. Gondwana Res. doi: 10.1016/j.gr.2023.06.006.

Destek MA, Oguz IH, Okumuş N. 2023. Do trade and financial cooperation improve environmentally sustainable development: a distinction between de facto and de jure globalization. Eval Rev. 0193841X231181747. doi: 10.1177/0193841X231181747.

Destek MA, Sarkodie SA. 2019. Investigation of environmental Kuznets curve for ecological footprint: the role of energy and financial development. Sci Total Environ. 650:2483–2489. doi: 10.1016/j.scitotenv.2018.10.017.

Destek MA, Sinha A, Ozsoy FN, Zafar MW. 2023. Capital flow and environmental quality at crossroads: designing a sustainable policy framework for the newly industrialized countries. Environ Sci Pollut R. 1–14. doi: 10.1007/s11356-023-27794-5.

Destek MA, Sohag K, Aydın S, Destek G. 2023. Foreign direct investment, stock market capitalization, and sustainable development: relative impacts of domestic and foreign capital. Environ Sci Pollut R. 30(11):28903–28915. doi: 10.1007/s11356-022-24066-6.

Dumitrescu EI, Hurlin C. 2012. Testing for Granger non-causality in heterogeneous panels. Econ Model. 29(4):1450–1460. doi: 10.1016/j.econmod.2012.02.014.

Duval R. 2008. A taxonomy of instruments to reduce greenhouse gas emissions and their interactions. OECD Economics Department Working Papers No. 636. doi: 10.1787/236846121450.

Dzwigol H, Kwilinski A, Lyulyov O, Pimonenko T. 2023. The role of environmental regulations, renewable energy, and energy efficiency in finding the path to green economic growth. Energies. 16(7):3090. doi: 10.3390/en16073090.

Elliott RJ, Sun P, Chen S. 2013. Energy intensity and foreign direct investment: a Chinese city-level study. Energy Econ. 40:484–494. doi: 10.1016/j.eneco.2013.08.004.

Gao J, Gao F, Yin B, Zhang M. 2021. International trade as a double-edged sword: the perspective of carbon emissions. Front Energy Res. 9:764914. doi: 10.3389/fenrg.2021.764914.

Gu X, Shen X, Zhong X, Wu T, Rahim S. 2023. Natural resources and undesired productions of environmental outputs as green growth: EKC in the perspective of green finance and green growth in the G7 region. Resour Policy. 82:103552. doi: 10.1016/j.resourpol.2023.103552.

Hassan T, Song H, Kirikkaleli D. 2022. International trade and consumption-based carbon emissions: evaluating the role of composite risk for RCEP economies. Environ Sci Pollut R. 29(3):3417–3437. doi: 10.1007/s11356-021-15617-4.

Jahanger A, Usman M. 2023. Investigating the role of information and communication technologies, economic growth, and foreign direct investment in the mitigation of ecological damages for achieving sustainable development goals. Eval Rev. 47(4):653–679. doi: 10.1177/0193841X221135673.

Jahanger A, Zaman U, Hossain MR, Awan A. 2023. Articulating CO2 emissions limiting roles of nuclear energy and ICT under the EKC hypothesis: an application of non-parametric MMQR approach. Geosci Front. 14(5):101589. doi: 10.1016/j.gsf.2023.101589.

Janipour Z, de Nooij R, Scholten P, Huijbregts MA, de Coninck H. 2020. What are sources of carbon lock-in in energy-intensive industry? A case study into Dutch chemicals production. Energy Res Social Sci. 60:101320. doi: 10.1016/j.erss.2019.101320.

Jiang R, Liu B. 2023. How to achieve carbon neutrality while maintaining economic vitality: an exploration from the perspective of technological innovation and trade openness. Sci Total Environ. 868:161490. doi: 10.1016/j.scitotenv.2023.161490.

Khan Z, Ali S, Umar M, Kirikkaleli D, Jiao Z. 2020. Consumption-based carbon emissions and international trade in G7 countries: the role of environmental innovation and renewable energy. Sci Total Environ. 730:138945. doi: 10.1016/j.scitotenv.2020.138945.

Kim SE, Seok JH. 2023. The impact of foreign direct investment on CO2 emissions considering economic development: evidence from South Korea. J Int Trade Econ Dev. 32(4):537–552. doi: 10.1080/09638199.2022.2122538.

Leitão NC, Balsalobre-Lorente D, Cantos-Cantos JM. 2021. The impact of renewable energy and economic complexity on carbon emissions in BRICS countries under the EKC scheme. Energies. 14(16):4908. doi: 10.3390/en14164908.

Leitão NC, Dos Santos Parente CC, Balsalobre-Lorente D, Cantos Cantos JM. 2023. Revisiting the effects of energy, population, foreign direct investment, and economic growth in Visegrad countries under the EKC scheme. Environ Sci Pollut R. 30(6):15102–15114. doi: 10.1007/s11356-022-23188-1.

Lei W, Xie Y, Hafeez M, Ullah S. 2022. Assessing the dynamic linkage between energy efficiency, renewable energy consumption, and CO 2 emissions in China. Environ Sci Pollut R. 29(13):1–13. doi: 10.1007/s11356-021-17145-7.

Liguo X, Ahmad M, Khan S, Haq ZU, Khattak SI. 2023. Evaluating the role of innovation in hybrid electric vehicle-related technologies to promote environmental sustainability in knowledge-based economies. Technol Soc. 102283:102283. doi: 10.1016/j.techsoc.2023.102283.

Liu C, Ni C, Sharma P, Jain V, Chawla C, Shabbir MS, Tabash MI. 2022. Does green environmental innovation really matter for carbon-free economy? Nexus among green technological innovation, green international trade, and green power generation. Environ Sci Pollut R. 29(45):67504–67512. doi: 10.1007/s11356-022-22040-w.

Lu Z, Mahalik MK, Mallick H, Zhao R. 2022. The moderating effects of democracy and technology adoption on the relationship between trade liberalisation and carbon emissions. Technol Forecast Soc. 180:121712. doi: 10.1016/j.techfore.2022.121712.

Machado JA, Silva JS. 2019. Quantiles via moments. J Econom. 213(1):145–173. doi: 10.1016/j.jeconom.2019.04.009.

Mahmood H, Alkhateeb TTY, Furqan M. 2020. Exports, imports, foreign direct investment and CO2 emissions in North Africa: spatial analysis. Ener Rep. 6:2403–2409. doi: 10.1016/j.egyr.2020.08.038.

Manga M, Cengiz O, Destek MA. 2023. Is export quality a viable option for sustainable development paths of Asian countries? Environ Sci Pollut R. 30(17):50022–50045. doi: 10.1007/s11356-023-25784-1.

Pata UK, Dam MM, Kaya F. 2023. How effective are renewable energy, tourism, trade openness, and foreign direct investment on CO2 emissions? An EKC analysis for ASEAN countries. Environ Sci Pollut R. 30(6):14821–14837. doi: 10.1007/s11356-022-23160-z.

Pegkas P. 2015. The impact of FDI on economic growth in eurozone countries. J Econ Asymmetries. 12(2):124–132. doi: 10.1016/j.jeca.2015.05.001.

Pesaran MH. 2004. General diagnostic tests for cross-sectional dependence in panels. Empir Econ. 60(1):13–50. doi: 10.1007/s00181-020-01875-7.

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

Pesaran MH. 2007. A simple panel unit root test in the presence of cross-section dependence. J of Appl Econ. 22(2):265–312. doi: 10.1002/jae.951.

Pesaran MH, Yamagata T. 2008. Testing slope homogeneity in large panels. J Econom. 142(1):50–93. doi: 10.1016/j.jeconom.2007.05.010.

Ponce P, Khan SAR. 2021. A causal link between renewable energy, energy efficiency, property rights, and CO2 emissions in developed countries: a road map for environmental sustainability. Environ Sci Pollut R. 28:37804–37817. doi: 10.1007/s11356-021-12465-0.

Popescu GH. 2014. FDI and economic growth in central and Eastern Europe. Sustainability. 6(11):8149–8163. doi: 10.3390/su6118149.

Qing L, Dagestani AA, Shinwari R, Chun D. 2023. Novel research methods to evaluate renewable energy and energy-related greenhouse gases: evidence from BRICS economies. Econ Res-Ekon Istraz. 36(1):960–976. doi: 10.1080/1331677X.2022.2080746.

Qin L, Hou Y, Miao X, Zhang X, Rahim S, Kirikkaleli D. 2021b. Revisiting financial development and renewable energy electricity role in attaining China's carbon neutrality target. J Environ Manage. 297:113335. doi: 10.1016/j.jenvman.2021.113335.

Qin L, Raheem S, Murshed M, Miao X, Khan Z, Kirikkaleli D. 2021a. Does financial inclusion limit carbon dioxide emissions? Analyzing the role of globalization and renewable electricity output. Sustain Dev. 29(6):1138–1154. doi: 10.1002/sd.2208.

Rasoulinezhad E, Taghizadeh-Hesary F. 2022. Role of green finance in improving energy efficiency and renewable energy development. Energ Effic. 15(2):14. doi: 10.1007/s12053-022-10021-4.

Sadiq M, Kannaiah D, Yahya Khan G, Shabbir MS, Bilal K, Zamir A. 2023. Does sustainable environmental agenda matter? The role of globalization toward energy consumption, economic growth, and carbon dioxide emissions in South Asian countries. Environ Dev Sustain. 25(1):76–95. doi: 10.1007/s10668-021-02043-2.

Sadorsky P. 2012. Energy consumption, output and trade in South America. Energy Econ. 34(2):476–488. doi: 10.1016/j.eneco.2011.12.008.

Shahbaz M, Loganathan N, Zeshan M, Zaman K. 2015. Does renewable energy consumption add in economic growth? An application of auto-regressive distributed lag model in Pakistan. Renew Sust Energ Rev. 44:576–585. doi: 10.1016/j.rser.2015.01.017.

Shah WUH, Hao G, Yan H, Zhu N, Yasmeen R, Dincă G. 2023. Role of renewable, non-renewable energy consumption and carbon emission in energy efficiency and productivity change: evidence from G20 economies. Geosci Front 101631. 101631. doi: 10.1016/j.gsf.2023.101631.

Shahzad U, Radulescu M, Rahim S, Isik C, Yousaf Z, Ionescu SA. 2021. Do environment-related policy instruments and technologies facilitate renewable energy generation? Exploring the contextual evidence from developed economies. Energies. 14(3):690. doi: 10.3390/en14030690.

Tao Y, Destek MA, Pata UK, Khan Z. 2023. Environmental regulations and carbon emissions: the role of renewable energy research and development expenditures. Sustainability. 15(18):13345. doi: 10.3390/su151813345.

Tariq G, Sun H, Ali I, Pasha AA, Khan MS, Rahman MM, Mohamed A, Shah Q. 2022. Influence of green technology, green energy consumption, energy efficiency, trade, economic development and FDI on climate change in South Asia. Sci Rep. 12(1):16376. doi: 10.1038/s41598-022-20432-z.

Udemba EN, Magazzino C, Bekun FV. 2020. Modeling the nexus between pollutant emission, energy consumption, foreign direct investment, and economic growth: new insights from China. Environ Sci Pollut R. 27(15):17831–17842. doi: 10.1007/s11356-020-08180-x.

Van Alstine J, Neumayer E. 2010. The environmental Kuznets curve. Handbook On Trade And The Environment. 2(7):49–59.

Wahab S. 2021. Does technological innovation limit trade-adjusted carbon emissions? Environ Sci Pollut R. 28(28):38043–38053. doi: 10.1007/s11356-021-13345-3.

Wang C, Xia M, Wang P, Xu J. 2022. Renewable energy output, energy efficiency and cleaner energy: evidence from non-parametric approach for emerging seven economies. Renew Energ. 198:91–99. doi: 10.1016/j.renene.2022.07.154.

Wang Q, Yang T, Li R. 2023. Does income inequality reshape the environmental Kuznets curve (EKC) hypothesis? A nonlinear panel data analysis. Environ Res. 216:114575. doi: 10.1016/j.envres.2022.114575.

Wei J, Rahim S, Wang S. 2022. Role of environmental degradation, institutional quality, and government health expenditures for human health: evidence from emerging seven countries. Fron Pub Healt. 10:10. doi: 10.3389/fpubh.2022.870767.

Wenlong Z, Tien NH, Sibghatullah A, Asih D, Soelton M, Ramli Y. 2023. Impact of energy efficiency, technology innovation, institutional quality, and trade openness on greenhouse gas emissions in ten Asian economies. Environ Sci Pollut R. 30(15):43024–43039. doi: 10.1007/s11356-022-20079-3.

Westerlund J. 2007. Testing for error correction in panel data. Oxf Bull Econ Stat. 69(6):709–748. doi: 10.1111/j.1468-0084.2007.00477.x.

Xia W, Apergis N, Bashir MF, Ghosh S, Doğan B, Shahzad U. 2022. Investigating the role of globalization, and energy consumption for environmental externalities: empirical evidence from developed and developing economies. Renew Energ. 183:219–228. doi: 10.1016/j.renene.2021.10.084.

Xu Y, Dong B, Chen Z. 2022. Can foreign trade and technological innovation affect green development: evidence from countries along the belt and road. Econ Change Restruct. 55(2):1063–1090. doi: 10.1007/s10644-021-09337-5.

Yabuki S. 2018. China's new political economy. revised ed. New York: Routledge. doi: 10.4324/9780429501692.

Yi M, Lu Y, Wen L, Luo Y, Xu S, Zhang T. 2022. Whether green technology innovation is conducive to haze emission reduction: empirical evidence from China. Environ Sci Pollut R. 1–13. doi: 10.1016/j.eneco.2022.106307.

You C, Khattak SI, Ahmad M. 2023. Impact of innovation in solar photovoltaic energy generation, distribution, or Transmission-related technologies on carbon dioxide emissions in China. J Knowl Econ. 1–35. doi: 10.1007/s13132-023-01284-y.

Zhou R, Zhen L, Li L, Iqbal N, Fareed Z. 2023. Energy efficiency and China's carbon emissions: evidence from non-parametric approaches. Energ Effic. 16(6):63. doi: 10.1007/s12053-023-10142-4.