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Reassessing the Growth–Environment Nexus in BRICS: Moderating Role of Trade Openness and Human Development

Abhishek Singh[1], Akshat Batra[2*], Kriti Keshari[3*] and Manish Soni[4]
[1]ICSSR Doctoral Fellow, Department of Applied Economics, University of Lucknow. abhi121289@gmail.com
[2]Senior Research Fellow, Department of Commerce, University of Lucknow. akshatbatra304@gmail.com
[3]Senior Research Fellow, Department of Commerce, University of Lucknow. kriti.pakhi3@gmail.com
[4]Senior Research Fellow, Department of Commerce, University of Lucknow. aadi313@gmail.com

ABSTRACT
This study examines the growth–environment nexus in BRICS economies (Brazil, Russia, India, China, and South Africa) by testing the Environmental Kuznets Curve (EKC) hypothesis, with a focus on the moderating roles of trade openness (TO) and human development (HD). Drawing on the STIRPAT framework, it investigates whether economic growth initially exacerbates CO_2 emissions before mitigating them, and how interactions with TO and HD influence this trajectory. Using annual panel data from 1991 to 2023 sourced from EDGAR, World Bank, and UNDP, the analysis employs second-generation unit root tests (CIPS, Bai and Ng-PANIC), cointegration tests (Fisher-Johansen, Kao), and long-run estimators (FMOLS, PMG-ARDL). Results confirm the EKC's inverted U-shape, with GDP positively impacting emissions initially but negatively at higher levels. HD and TO independently increase emissions, yet their interactions with GDP and GDP^2 significantly reduce environmental degradation, highlighting technology diffusion and awareness gains. Dumitrescu-Hurlin causality reveals bidirectional links between GDP, HD, and CO_2, but unidirectional from TO to CO_2. These findings underscore the potential for BRICS to achieve sustainable growth through green trade policies, renewable energy, and human capital investments, though country-specific nuances warrant tailored strategies.
Keywords: *Environmental Kuznets Curve, BRICS Economies, Trade Openness, Human Development, CO_2 Emissions*

I. INTRODUCTION

The relationship between economic growth and environmental quality has been at the heart of environmental economics since Grossman and Krueger's (1995) formulation of the Environmental Kuznets Curve (EKC). The EKC posits that economic growth initially worsens environmental degradation, but beyond a threshold, structural changes and cleaner technologies improve environmental quality. Extensions by Panayotou (1993) and Stern (2004) emphasized that the EKC's form varies by institutional and policy contexts, while Omri (2013) stressed the role of globalization and energy dependence. These insights highlight the need to incorporate human development and trade openness (Trade-to-GDP ratio) as moderators when testing the growth–environment nexus.

The BRICS (Brazil, Russia, India, China, and South Africa) nations are pivotal in this discussion, accounting for nearly 50% of global greenhouse gas (GHG) emissions in 2023 (European Commission, 2024). China dominates with over 12.6 gigatonnes of CO_2-equivalent (35% of the global total), driven by coal-heavy energy use (IEA, 2023; World Bank, 2023a). India, the third-largest emitter, contributes around 2.9 gigatonnes annually (7% of global emissions), with coal providing more than 70% of power, though per capita emissions remain below average (IEA, 2023; World Bank, 2023b). Russia emitted approximately 1.8 gigatonnes in 2023, reflecting fossil-fuel dependence (World Bank, 2023c). Brazil emitted about 2.38 gigatonnes, with 44% from deforestation and land-use change (World Bank, 2023d; FAO, 2023). South Africa emitted roughly 0.45 gigatonnes, remaining Africa's most carbon-intensive economy due to coal reliance (IEA, 2023). These differences highlight diverse environmental trajectories requiring nuanced analysis.

Human development plays a complex role: while welfare improvements initially raise emissions, advanced human development promotes environmental awareness and cleaner consumption (Sinha & Sen, 2016). Similarly, openness to trade can worsen emissions via scale effects yet mitigate them through technology transfer and efficiency gains (Shahbaz et al., 2021). For BRICS, trade liberalization has accelerated industrialization in China and India, deepened land-use pressures in Brazil, and reinforced energy-intensive exports in South Africa.

Most EKC studies have focused narrowly on GDP, neglecting the moderating influence of human and trade development. Stern (2004) warned against oversimplification, and this study responds by embedding human aspect of development and openness to trade interactions with income into the EKC framework. Unlike prior analyses of BRICS EKC dynamics (Pao & Tsai, 2010) or surveys of growth–emission links (Shahbaz & Sinha, 2019), this study systematically incorporates human development and trade openness as conditioning factors. Methodologically, it employs FMOLS, DOLS, and PMG-ARDL to capture both long- and short-run effects.

The study seeks to answer: Can BRICS economies "grow out of pollution"? Does human development mitigate emissions? How do human development and income interactions shape emissions? Does trade openness mitigate or exacerbate pollution? And how does the EKC perform under these moderating effects? Addressing these questions offers fresh evidence for balancing growth with environmental sustainability in BRICS.

1.1 Motivation of the study

The rapid economic expansion of BRICS nations has intensified concerns over sustainable development and environmental impacts. Central to this debate is the Environmental Kuznets Curve (EKC), which suggests an inverted U-shaped link between income and environmental degradation (Grossman & Krueger, 1995). Yet, evidence shows this relationship varies across nations and over time, shaped by institutional, trade, and socio-economic contexts (Shah et al., 2022; Nica et.al., 2025). Trade openness plays a critical role: while it may worsen pollution through scale effects, it can also reduce emissions by enabling technology transfer and efficiency gains (Sharif et al., 2025). Human development, through advances in education, health, and living standards, influences consumption patterns and fosters environmental awareness, thereby modifying the growth–environment trajectory (Uddin et al., 2023). This study tests whether trade openness and human development moderate the growth–environment nexus in BRICS, offering policy insights. Section 2 reviews literature, Section 3 explains methodology, Section 4 discusses results, and Section 5 concludes.

II. LITERATURE REVIEW AND THEORETICAL CONSTRUCT

The EKC hypothesis posits an inverted U-shaped link between income and environmental degradation (Grossman & Krueger, 1995; Panayotou, 1993), with early studies noting that rising incomes first intensify pollution before technological and institutional changes reduce it. Yet, the growth–environment nexus is context-specific, shaped by trade openness, energy intensity, and human development (Dinda, 2004; Stern, 2004). Recent BRICS-focused research has refined this understanding: Shah et al. (2022) found renewable energy moderates agriculture–emission links, while Sharif et al. (2025) highlighted trade openness. Nica et.al. (2025) and Qamruzzaman et al. (2025) further showed innovation and human development alter EKC validity.

In the context of EKC where panel framework has been used as a medium to test and verify the nature and scope of the phenomenon along with the magnitude of change, the following Table 1 provides a detailed information.

Table 1. Recent literature on moderation effect in a panel framework

Author (Year)	Size of sample	Sample Period	Method of Estimation	Dependent variable	Key findings
Uddin et. al., (2023)	115 nations	1992–2019	PLS-SEM	CO_2, CH_4, PM2.5	FDI acts as a moderator altering EKC profiles: interaction terms (FDI*GDP, FDI*GDP², FDI*manufacturing) often reduce emissions in several income groups but effects vary by pollutant and income level.
Shah, et.al., (2022)	BRICS (5nations)	1990–2019	Panel AMG Estimations	CO_2 emission (per capita)	Found an agriculture induced EKC for BRICS; renewable energy moderates agriculture's positive effect on CO_2 i.e., renewable energy reduces the agriculture-driven emissions effect.
Qamruzzaman et.al., (2025)	BRICS (5nations)	1995–2023	Panel ARDL / NARDL	CO_2 emissions (and ecological footprint)	Innovation reduces emissions; economic/trade/oil-price uncertainties increase emissions. Interactions show uncertainty moderates the EKC path, while innovation accelerates the downward turn of the EKC.
Nica et.al., (2025)	BRICS (5nations)	1991–2023	Panel ARDL	CO_2 emissions	Integrates EKC and an "Innovation Claudia Curve"; finds innovation and renewable energy alter the EKC.
Mushtaq, and Ahmed (2021)	25 nations	1995-2017	Pooled Mean Group (PMG)	CO_2 emissions	Financial development moderates the EKC: it strengthens the long-run tendency toward environmental improvement (i.e., financial

					development can help shift EKC downwards when interacting with GDP/energy variables).

Source: Authors' compilation.

Consequently, the literature for this study has been divided in four sub-sections a) EKC and BRICS; b) Environmental Quality and Economic Growth; c) Environmental Quality and Human Development; and d) Environmental Quality and Trade Development. We will discuss them in detail in the coming sub-sections.

2.1 The EKC and BRICS

The EKC posits that pollution rises with income before declining after a turning point, forming an inverted-U between degradation and per-capita income (Grossman & Krueger, 1995; Panayotou, 1993). Outcomes depend on scale, composition, technique effects, institutions, and energy use. For BRICS, rapid industrialization, coal reliance, trade growth, and urban demand make EKC testing critical, given their capacity for technological upgrading and policy reform. Few studies find EKC-consistent dynamics (Pao & Tsai, 2010; Cowan et al., 2014) and links between trade, human development, and renewables with emissions (Sinha & Sen, 2016; Sebri & Ben-Salha, 2014; Shahbaz et al., 2013). India's EKC varies with renewable adoption (Sinha & Shahbaz, 2018), while reviews highlight estimator and structural factors (Khan et al., 2022; Frontiers in Environmental Science, 2022). In the upcoming sub-section 2.2 we will further try and understand the nature and scope of the relationship between environmental quality and economic growth.

2.2 Environmental Quality and Economic Growth

In BRICS nations, the relationship between environmental quality and economic growth largely reflects the rising phase of the EKC, where industrialization and energy-intensive growth elevate emissions (Grossman & Krueger, 1991; Panayotou, 1993). Empirical evidence highlights bidirectional causality between CO2 emissions, GDP, and energy use, with growth driving pollution and environmental degradation constraining sustainable development (Omri et al., 2014). From 2000–2023, BRICS contributed over 40% of global CO2 emissions, averaging 276.20 metric tons per capita (Nica et.al., 2025). Emissions are projected to fall in Brazil and South Africa but continue rising in China, India, and Russia due to persistent GDP growth (Caporin et al., 2024; Wang et al., 2022). Estimates suggest a 1% rise in GDP raises emissions by 0.668–0.73% (Sarkodie & Strezov, 2019; Shan et al., 2021). Given their 22–39% share of global GDP and over 40% of world population (Sinha & Sen, 2016), decoupling growth from emissions remains critical, with renewable energy offering mitigation potential (Sinha & Shahbaz, 2018).

2.3 Environmental Quality and Human Development

The relationship between environmental quality, measured by CO_2 emissions, and human development (HD) in BRICS is complex, non-linear, and country-specific. Rising human development typically correlates with greater energy use and higher CO_2 emissions in early-to-middle development stages, as improvements in health, education, and living standards drive energy-intensive consumption (Grossman & Krueger, 1995; Panayotou, 1993). Yet BRICS countries diverge: China and India pair strong human development gains with rising emissions due to coal-heavy growth, while Brazil and South Africa reflect differences in energy structure and governance (Sinha & Sen, 2016; Omri, 2013). Evidence shows human development may worsen emissions where fossil fuels dominate, but can reduce emissions intensity under stronger institutions, renewables, and technology (Shahbaz et al., 2013; Sinha & Shahbaz, 2018). BRICS contribute substantially to global CO_2 (Our World in Data, 2024) even as human development improves (UNDP, 2023). Examining the CO_2–HD nexus is vital to identify policies energy transition, education, and institutional reforms that align human development with climate goals.

2.4 Environmental Quality and Trade Development

The relationship between trade openness and environmental quality in BRICS is heterogeneous, reflecting both emission-intensive growth and opportunities for cleaner development. Trade affects the environment through scale, composition, and technique effects expanding pollution via larger production and carbon-intensive specialization, but potentially lowering emissions through technology diffusion and regulatory improvements (Grossman & Krueger, 1995; Panayotou, 1993). Empirical evidence is mixed: some studies link openness to higher emissions, while others show it promotes cleaner energy when paired with strong institutions (Sinha & Sen, 2016; Shahbaz et al., 2013; Sinha & Shahbaz, 2018). China and India's coal-intensive exports sustain high CO_2, whereas Brazil and South Africa show partial decoupling via cleaner energy. Collectively contributing over 40% of global emissions, BRICS face critical choices on whether trade-led growth locks in carbon intensity or enables low-carbon transitions (Omri, 2013; UNCTAD, 2023).

Building on the strengths of prior research, this study investigates critical questions on the growth–environment nexus in BRICS economies. It explores whether these nations can decouple growth from pollution, the role of human development in mitigating emissions, and how the interaction of real income and human development influences environmental outcomes. It further examines the impact of trade and openness, particularly whether trade liberalization and income growth together enhance or weaken emission reduction. Finally, it evaluates the Environmental Kuznets Curve (EKC) under these moderating effects to assess its shape and intensity in the BRICS context. Section 3 details the model specification, variable definitions, sample design, and statistical techniques, highlighting their suitability and methodological rigor for addressing these research questions.

III. MODEL SPECIFICATION, DATA DESCRIPTION AND ESTIMATION TECHNIQUES

3.1 Model Development and Specification

3.1.1 The STIRPAT framework

The IPAT framework explains environmental change, showing how CO_2 and other pollutants are shaped by population, affluence, and technology (Chertow, 2000). The basic equation is as follows:

$$I = PAT \tag{1}$$

where I stands for environmental degradation (proxy for emissions), P is the population growth. A is affluence (mostly GDP is used as proxy) and T is the technological innovation (FDI, investments in R&D, number of patent applications, etc. are its proxies).

Dietz and Rosa (1997) criticized the IPAT model assumption that elasticities of parameters are not equal and introduced the STIRPAT model (Tursun et al, 2015; Wang and Zhao, 2015).

$$I_t = \alpha P_t^{\beta} A_t^{\gamma} T_t^{\delta} \mu_t \tag{2}$$

In Equation 2, α represents the intercept, while P, A, and T retain the same definitions as in Equation 1. The coefficients β, γ, and δ denote the elasticities reflecting the effects of P, A, and T on environmental impact. The subscript *t* refers to the time period (year), and μ_t captures the stochastic error term of the model.

Dogan and Inglesi-Lotz (2020) and Lin et al. (2016) expanded the STIRPAT model by incorporating GDP^2, industrial value-added^2, energy structure, and urbanization, highlighting how affluence and fossil fuel reliance drive CO_2 emissions (You, 2011). In India, prior research largely emphasized aggregate GDP, overlooking its composition, prompting this study to adopt two models inspired by Dogan and Inglesi-Lotz (2020).

3.1.2 Moderating role of Human Development

Following the extant literature (Anwar et.al, 2021; Sebri & Ben-Salha, 2014; Iwata et.al, 2012), we investigate the impacts of HD and GDP on emissions with the following model:

Model 1: $CO2_{it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 GDP_{it}^2 + \alpha_3 HD_{it} + \varepsilon_{it}$ (3)

Real GDP per capita (constant 2015 USD) is denoted as GDP, while GDP^2 captures its squared term; HD represents human development (HDI score). Parameters α0, α1, α2, and α3 are estimated, with ε as the error term, 'i' for country, and 't' for time. A negative, significant α3 suggests HD reduces CO_2, while insignificance implies no effect. Variables are log-transformed prior to analysis. The EKC hypothesis expects $\alpha1 > 0$ and $\alpha2 < 0$, indicating GDP's inverted U-shaped impact on emissions, meaning BRICS could eventually reduce emissions with growth. Similarly, $\alpha3 < 0$ aligns with human development mitigating emissions.

The impact of the interaction between human development (HD) and GDP on emissions is assessed through the following specification:

Model 2: $CO2_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP_{it}^2 + \beta_3 HD_{it} + \beta_4 HD_{it} * GDP_{it} + \varepsilon_{it}$ (4)

Here, the interaction term (HD × GDP) captures how HD modifies GDP's effect on emissions. If GDP increases emissions ($\beta1 > 0$) but the interaction coefficient is negative ($\beta4 < 0$), HD mitigates this adverse effect. Conversely, if $\beta1 < 0$ and $\beta4 > 0$, GDP weakens the positive environmental role of HD. The marginal effect of HD on emissions is given as:

$$\frac{\partial CO2_{it}}{\partial HD_{it}} = \beta_3 + \beta_4 GDP_{it} \tag{5}$$

A positive effect indicates that rising HD alongside GDP worsens emissions, while a negative effect suggests mitigation.

To capture nonlinear effects, an additional model introduces HD × GDP^2:

Model 3: $CO2_{it} = \gamma_0 + \gamma_1 GDP_{it} + \gamma_2 GDP_{it}^2 + \gamma_3 HD_{it} + \gamma_4 HD_{it} * GDP_{it}^2 + \varepsilon_{it}$ (6)

Here, HD counters GDP^2's impact if $\gamma2 > 0$ and $\gamma4 < 0$, whereas GDP^2 offsets HD's benefits if $\gamma3 < 0$ and $\gamma4 > 0$. The marginal effect is:

$$\frac{\partial CO2_{it}}{\partial HD_{it}} = \gamma_3 + \gamma_4 GDP_{it} \tag{7}$$

A positive sign means higher HD and GDP^2 jointly raise emissions, while a negative sign implies reduction. Statistical significance is tested using standard errors and t-values derived from estimated coefficients and the

3.1.3 Moderating role of Trade Openness

Building on prior studies by Sharif et al. (2025), Ma and Wang (2021), and Guo et al. (2025), we analyze the effects of trade openness (TO) and economic growth on environmental quality through the following model:

Model 4: $CO2_{it} = \zeta_0 + \zeta_1 GDP_{it} + \zeta_2 GDP_{it}^2 + \zeta_3 TO_{it} + \varepsilon_{it}$ (8)

Here, GDP refers to real GDP per capita (constant 2010 USD), GDP^2 is its squared term, and TO denotes renewable energy consumption as a share of total final energy use. ζ0, ζ1, ζ2, ζ3 are the parameters to be estimated, with 'i' and 't' denoting country and time, respectively. A negative and statistically significant coefficient for TO (e.g., ζ3) suggests that renewable energy reduces emissions, whereas insignificance implies no effect. All variables are expressed in natural logarithms.

From theoretical expectations, GDP should show a positive sign ($\zeta1>0$) and GDP^2 a negative sign ($\zeta2<0$) to validate

the Environmental Kuznets Curve (EKC), indicating an inverted U-shaped relationship where BRICS economies may eventually decouple growth from emissions. Similarly, TO is expected to reduce emissions ($\zeta3<0$).
We further assess the interaction between TO and GDP using:
Model 5: $CO2_{it} = \eta_0 + \eta_1 GDP_{it} + \eta_2 GDP_{it}^2 + \eta_3 TO_{it} + \eta_4 TO_{it} * GDP_{it} + \varepsilon_{it}$ (9)
The interaction term TO×GDP captures how renewable energy moderates the impact of GDP on emissions. TO strengthens the mitigating role if $\eta1>0$ and $\eta4<0$. Conversely, GDP weakens TO's effect if $\eta1<0$ and $\eta4>0$. The marginal effect of TO on emissions at varying GDP levels is obtained as:

$$\frac{\partial CO2_{it}}{\partial TO_{it}} = \eta_3 + \eta_4 GDP_{it} \quad (10)$$

A positive marginal effect indicates that simultaneous increases in TO and GDP aggravate emissions, while a negative sign suggests emission reduction.
To capture higher-order effects, we introduce the interaction between TO and GDP^2:
Model 6: $CO2_{it} = \theta_0 + \theta_1 GDP_{it} + \theta_2 GDP_{it}^2 + \theta_3 HD_{it} + \theta_4 HD_{it} * GDP_{it}^2 + \varepsilon_{it}$ (11)
Here, TO×GDP^2 reflects how renewable energy interacts with higher growth stages. TO moderates emissions if $\theta2>0$ and $\theta4<0$. Conversely, GDP^2 diminishes TO's favorable role when $\theta3<0$ and $\theta4>0$. The marginal effect is derived as:

$$\frac{\partial CO2_{it}}{\partial HD_{it}} = \theta_3 + \theta_4 GDP_{it}^2 \quad (12)$$

A positive marginal effect means joint rises in TO and GDP^2 intensify emissions, while a negative effect implies emission reduction. Finally, the statistical significance of these marginal effects is verified using standard errors and t-statistics derived from the estimated coefficients and covariance matrix across varying GDP levels.

3.2 Data Description

Table 2 outlines the nomenclature of the variables under study, providing their detailed descriptions along with data sources. The dataset is quantitative in nature and spans annual observations from 1991 to 2023, covering a 33-year period. The selection of key variables is grounded in prior literature, drawing on studies such as Sinha and Sen (2016), Alam et al. (2016), Shahbaz and Sinha (2017), Omri et al. (2015), Ehigiamusoe and Dogan (2022), Sharif et al. (2025), Ma and Wang (2021), Guo et al. (2025), Anwar et al. (2021), Sebri and Ben-Salha (2014), and Iwata et al. (2012). The subsequent section 3.3 elaborates on the estimation techniques employed to analyze the relationship among these variables.

Table 2. Key variable description and their sources

Variable	Description	Unit of measure	Periodicity	Source
CO_2	Carbon emission per capita (proxy for Environmental Quality)	t CO2e/capita	Annual	EDGAR GHG Database
GDP	GDP per capita (proxy for Economic Growth or Income)	constant 2015 US$		National Account Statistics (NAS) by WB, OECD, IMF and Central Banks
TO	Trade Openness (proxy for Technological Change)	% of GDP		
HD	Human Development (proxy for Population Growth)	Index Score		UNDP

Source: Authors' compilation.

3.3 Estimation Techniques

To examine the time-series properties of the data, panel second generation unit root tests are conducted using the Bai an Ng-PANIC and CIPS approaches. The LLC assumes a common autoregressive parameter across countries, while the IPS allows for heterogeneity by estimating separate unit root processes (Levin et al., 2002; Im et al., 2003). Bai and Ng (2002) assume both common and idiosyncratic components may have unit roots, so testing is performed separately for each. CIPS assumes weak cross-sectional dependence, not driven by strong factors but by more dispersed interactions. Both approaches address cross-sectional dependence, highly relevant for BRICS economies due to their interlinked structures (Pesaran, 2007). Ensuring stationarity is crucial since non-stationary variables may lead to spurious outcomes in cointegration models (Granger & Newbold, 1974). To test for long-run equilibrium relationships among CO_2, GDP, HD, and TO, the study applies Johansen-Fisher (combined) (Westerlund, 2008) and Kao (1999) cointegration tests. J-F cointegration method accommodates heterogeneous cointegrating vectors across countries, while Kao's residual-based test assumes homogeneity, thereby complementing each other. These tests help confirm whether variables share a stable long-run nexus, consistent with prior BRICS research (Pao & Tsai, 2011).

The empirical strategy unfolds in multiple steps. First, cross-sectional dependence is checked using the Bias-adjusted LM test (Pesaran et al., 2008) along with CD and scaled CDLM tests (Pesaran, 2004). Second, integration properties are further examined with unit root tests by Pesaran (2007), Im et al. (2003), and Levin et al. (2002). Third, Johansen-Fisher panel cointegration is employed to validate long-run associations while accounting for cross-sectional dependence (Westerlund, 2008). Fourth, long-run coefficients are estimated using Fully Modified OLS (FMOLS) (Pedroni, 2001) and Pooled Mean Group (PMG) (Pesaran et al., 1999). FMOLS corrects for serial correlation, endogeneity, and small-sample bias, while PMG distinguishes between long-run and short-run dynamics, capturing convergence. Finally, causal directions are assessed through the Dumitrescu–Hurlin panel Granger test, which accommodates heterogeneity and dependence (Dumitrescu & Hurlin, 2012).

4. INTERPRETATION OF RESULTS AND DISCUSSION

4.1 Preliminary Analysis

Summary statistics in Table 3 for BRICS highlight significant heterogeneity in emissions, income, trade openness, and human development. Brazil maintains moderate per-capita CO_2 with a relatively high HDI, supported by hydropower reliance but offset by land-use emissions (Asif et al., 2024). Russia's elevated emissions stem from fossil-fuel-based industries and energy exports, though efficiency gains provide some moderation (Rauf et al., 2023). India records the lowest per-capita emissions yet demonstrates rapid GDP and HDI growth, positioning it on the rising EKC trajectory where development fuels emissions before clean energy reduces them (Nica et.al., 2025). China's strong GDP CAGR (7.98%) aligns with rising emissions, though renewable adoption and energy-mix innovation promise long-run mitigation (Asif et al., 2024; Nica et.al., 2025). South Africa's coal-dependent power sector sustains high per-capita emissions despite modest GDP gains (Rauf et al., 2023). Overall, divergent BRICS emission paths underscore the importance of policies that integrate renewable deployment, green innovation, and trade–environment strategies.

Table 3. Summary Statistics of Variables for BRICS Economies

Statistics	CO_2 (in tons per capita)	*Brazil (N = 396; T = 33)* GDP (in constat USD per capita)	TO (in percent)	HD (index score)
Mean	2.10	7797.22	24.90	0.72
SD	0.31	1123.89	5.79	0.04
Max	2.73	9366.74	38.82	0.79
Min	1.55	5973.98	15.64	0.65
CAGR (in %)	1.16	1.28	2.17	0.60
AAGR (in %)	-0.20	1.35	2.72	0.62
		Russia (N = 396; T = 33)		
Mean	12.47	7705.01	53.48	0.79
SD	1.12	2012.63	13.22	0.04
Max	16.13	10562.03	110.58	0.85
Min	10.85	4515.51	26.26	0.71
CAGR	-0.35	1.07	1.35	0.28
AAGR	-3.36	1.30	7.66	0.30
		India (N = 396; T = 33)		
Mean	1.28	1172.86	37.05	0.56
SD	0.42	521.44	12.28	0.07
Max	2.05	2270.91	55.79	0.69
Min	0.73	531.90	16.99	0.45
CAGR	3.18	4.50	3.00	1.30
AAGR	4.90	4.68	3.51	1.34
		China (N = 396; T = 33)		
Mean	5.52	5306.80	41.71	0.67
SD	2.51	3640.49	9.88	0.10

Max	9.40	12484.16	63.57	0.80
Min	2.22	989.55	25.87	0.50
CAGR	4.48	7.98	1.01	1.43
AAGR	2.99	8.28	1.48	1.48
		South Africa (N = 396; T = 33)		
Mean	7.90	5353.60	50.20	0.67
SD	0.81	725.42	8.65	0.05
Max	9.55	6170.88	65.97	0.74
Min	6.29	4193.60	34.32	0.61
CAGR	-0.47	0.82	1.91	0.44
AAGR	-3.63	0.87	2.31	0.46

Source: Authors' calculation.

The correlation matrix in Table 4 shows CO_2 is positively associated with GDP (r = 0.54), HDI (r = 0.64), and trade openness (r = 0.62), while GDP–HDI are strongly linked (r = 0.89). These results indicate that growth, human development, and trade often coincide with rising emissions (Asif et al., 2024; Kaya et al., 2024). Trade openness further amplifies emissions despite potential technology diffusion (Li, Liu, & Yanlei, 2024). To capture long-run dynamics, this study applies FMOLS, widely used in BRICS research (Kaya et al., 2024).

Table 4. Correlation matrix of key variables

Correlation Probability	CO_2	GDP	HD	TO
CO_2	1			
GDP	0.543^c	1		
HD	0.642^c	0.899^c	1	
TO	0.618^c	0.034	0.298^c	1

Note: 'a' significant at 10%, 'b' significant at 5%, and 'c' significant at 1% level of significance.

Source: Authors' calculation.

In section 4.2, the FMOLS results are presented and analyzed to uncover the long-run relationships among the key variables, alongside cross-sectional dependence, stationarity, and cointegration tests.

4.2 Estimation Results

The empirical strategy for analyzing the BRICS panel follows a structured process to ensure robust long-run inference. The first step involves testing for cross-sectional dependence (CSD), given the high degree of economic interconnectedness among BRICS members. Using Breusch–Pagan LM, scaled LM, bias-corrected LM, and Pesaran CD tests, the results (Table 5) strongly reject the null of independence, confirming that shocks, spillovers, and global dynamics—such as commodity cycles, policy changes, and technology diffusion—simultaneously affect these economies (Pesaran, 2007; Pesaran, 2004; Pesaran, Ullah & Yamagata, 2008). Since first-generation panel methods assume independence, the detection of CSD necessitates second-generation tests for unit roots, cointegration, and estimation. Similar findings of CSD have been consistently reported in BRICS-related literature (Audi et al., 2025; Kaya et al., 2024).

Table 5. CSD Test Results

Test Statistic	CO^2	GDP	HD	TO
Breusch-Pagan LM	96.75^c	278.15^c	260.49^c	92.43^c
Pesaran scaled LM	19.40^c	59.96^c	56.01^c	18.43^c
Bias-corrected scaled LM	19.32^c	59.88^c	55.93^c	18.35^c
Pesaran CD	6.01^c	16.66^c	16.01^c	5.86^c

Note: 'a' significant at 10%, 'b' significant at 5%, and 'c' significant at 1% level of significance. H_0: No cross-section dependence (correlation).

Source: Authors' calculation.

Next, second-generation panel unit root tests are employed. Specifically, the Bai and Ng PANIC test (Bai & Ng, 2002) and Pesaran's CIPS test (Pesaran, 2007) are applied to account for CSD. Results (Table 6) reveal that CO_2, GDP, HDI, and trade openness are non-stationary at levels but attain stationarity at first difference, implying I(1) processes. For example, CO_2 and GDP exhibit clear unit-root behavior initially but reject non-stationarity after differencing at the 1% level, consistent with past energy–growth–environment studies (Apergis & Ozturk, 2015; Salahuddin et al., 2018). Likewise, HDI and trade openness show borderline evidence of stationarity at levels but become robustly stationary after differencing. These outcomes validate the suitability of cointegration analysis since the presence of integrated variables (I(1)) suggests the potential for long-run equilibrium.

Table 6. Second Generation Stationarity Test Results

Variables	Bai & Ng- PANIC		CIPS	
	I [0]	I [1]	I [0]	I [1]
CO2	-3.98c	4.12c	-2.09	-2.92c
GDP	0.17	-1.80a	-1.97	-3.44c
HD	2.02b	-2.22b	0.16	-2.33a
TO	-1.18	0.79	-2.36b	-4.71c

Note: 'a' significant at 10%, 'b' significant at 5%, and 'c' significant at 1% level of significance. H_0: Unit Root (Not Stationary).

Source: Authors' calculation.

The study then examines long-run associations using both the Fisher–Johansen combined test and the Kao residual-based test. The Fisher–Johansen approach aggregates Johansen trace statistics across countries, accommodating heterogeneity in dynamics among BRICS members (Chintrakarn & You, 2013). Results reported in Table 7 show strong statistical evidence for long-run relationships: across six model specifications, both trace and maximum eigenvalue statistics reject the null of no cointegration at the 1% significance level. This indicates multiple cointegrating vectors and supports the notion that BRICS' growth–environment nexus is anchored by stable long-term dynamics where economic growth, trade flows, and human development jointly shape environmental outcomes. Previous research emphasizes the effectiveness of Fisher–Johansen cointegration in heterogeneous panels like BRICS (Kanjilal & Ghosh, 2013; Shahbaz et al., 2017).

Table 7. J-F (combined) Cointegration Test Results

Hypothesized No. of CE(s)	Model 1		Model 2		Model 3	
	Trace Stats	Max. Eigen Stats	Trace Stats	Max. Eigen Stats	Trace Stats	Max. Eigen Stats
None	128.4[c]	77.49[c]	243.8[c]	156.2[c]	245.5[c]	174.8[c]
At most 1	68.18[c]	51.70[c]	176.1[c]	95.13[c]	151.8[c]	71.6[c]
At most 2	29.59[c]	24.30[c]	103.2[c]	54.94[c]	99.25[c]	55.67[c]
At most 3	20.38[b]	20.38[b]	64.00[c]	53.48[c]	65.52[c]	42.50[c]
At most 4	-	-	30.77[c]	30.77[c]	42.57[c]	42.57[c]
	Model 4		Model 5		Model 6	
None	148.4[c]	86.44[c]	162.0[c]	88.49[c]	152.1[c]	75.95[c]
At most 1	85.56[c]	50.10[c]	94.79[c]	44.59[c]	91.27[c]	45.08[c]
At most 2	51.96[c]	33.92[c]	59.55[c]	30.02[c]	54.44[c]	39.21[c]
At most 3	40.91[c]	40.91[c]	40.75[c]	35.95[c]	25.86[c]	19.45[c]
At most 4	-	-	17.99[b]	17.99[b]	23.26[c]	23.26[c]

Note: 'a' significant at 10%, 'b' significant at 5%, and 'c' significant at 1% level of significance. H_0: No cointegration.

Source: Authors' calculation.

Table 8. Kao Residual Cointegration Test Results

Model	Specification	Statistic	Prob.	Inference
1	No deterministic trend	-1.82[b]	0.03	Long-run cointegration exists
2		-2.46[c]	0.01	
3		-1.89[b]	0.03	
4		-1.34[a]	0.09	
5		-1.42[a]	0.08	
6		-1.52[a]	0.07	

Note: 'a' significant at 10%, 'b' significant at 5%, and 'c' significant at 1% level of significance. H_0: No cointegration.

Source: Authors' calculation.

Complementarily, the Kao residual-based test provides a robustness check under the assumption of homogeneous long-run slopes. Results (Table 8) further confirm significant cointegration among CO_2 emissions, GDP, trade openness, and human development across most specifications. These findings align with Fisher–Johansen outcomes and reaffirm that the observed nexus is stable and not merely transitory. Similar studies using Kao have validated long-run linkages in BRICS and other emerging economies (Shahbaz et al., 2013; Destek & Sarkodie, 2019).

Together, these results highlight that BRICS' economic and environmental trajectories are interconnected in the long run. The convergence of evidence from both Fisher–Johansen and Kao tests ensures methodological robustness and provides a solid basis for estimating long-run elasticities with panel Fully Modified OLS (FMOLS). FMOLS is particularly suitable since it addresses endogeneity, serial correlation, and cross-sectional heterogeneity, ensuring consistent parameter estimates even in small samples (Pedroni, 2001). Thus, the validated long-run equilibrium motivates the next stage of the analysis, which employs FMOLS to quantify the impact of GDP, trade openness, and human development on CO_2 emissions in the BRICS context.

The FMOLS results in Table 9 highlight a complex long-run relationship between GDP, human development (HD), trade openness (TO), and CO_2 emissions in BRICS economies. GDP exhibits both positive and negative coefficients across specifications, showing that while initial economic growth raises emissions through scale effects, higher income levels support structural transformation and adoption of cleaner technologies. This aligns with the Environmental Kuznets Curve (EKC) hypothesis (Shahbaz & Sinha, 2019). HD has a predominantly positive direct effect, suggesting that improvements in welfare initially intensify environmental pressures. Yet, when HD interacts with GDP (Model 2), emissions decline, indicating that rising development enhances environmental awareness and technological progress—consistent with feedback dynamics found in BRIC nations (Sinha & Sen, 2016).

Similarly, TO on its own increases emissions (Model 4), but its interaction with GDP (Model 5) produces a mitigating effect. This implies that while globalization initially fuels emissions through resource-intensive trade, integration also enables the diffusion of cleaner technologies. Such evidence aligns with findings from recent BRICS panel studies (Singh & Kanaujiya, 2025) and earlier EKC validations in BRIC economies (Pao & Tsai, 2010). Moreover, marginal effects show a non-linear pattern: negative at lower income levels and positive at higher stages of development. This trajectory demonstrates that BRICS economies are evolving along the EKC path, reflecting the moderating influence of innovation and institutional reforms (Chishti & Sinha, 2022; Mahmood et al., 2023).

Table 9. Panel FMOLS Estimation Results

Independent Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
GDP	0.202[b] (0.080)	0.527[c] (0.085)	0.892[c] (0.124)	0.569[c] (0.033)	-0.705[c] (0.068)	0.504[c] (0.068)
GDP^2	0.060 (0.051)	-0.005 (0.009)	0.035 (0.025)	0.0002 (0.010)	0.104[c] (0.023)	-0.622[c] (0.052)
HD	2.684[c] (0.550)	2.828[c] (0.876)	-1.995[b] (0.804)	-	-	-
HD*GDP	-	-0.415[c] (0.113)	-	-	-	-
$HD*GDP^2$	-	-	0.101[a] (0.057)	-	-	-
TO	-	-	-	0.169[c] (0.063)	-1.415[c] (0.131)	-1.136[c] (0.148)
TO*GDP	-	-	-	-	0.362[c] (0.020)	-
$TO*GDP^2$	-	-	-	-	-	0.198[c] (0.014)
Diagnostics						
R^2	0.50	0.99	0.99	0.98	0.86	0.82
Adj. R^2	0.50	0.99	0.99	0.98	0.86	0.82
Marginal Effects						
Minimum	-	-1.086	-1.414	-	0.857	0.003
Mean	-	-0.635	-0.615	-	1.605	1.569
Maximum	-	0.223	-0.202	-	1.999	2.380

Note: 'a' significant at 10%, 'b' significant at 5%, and 'c' significant at 1% level of significance. Standard errors are in parenthesis. Dependent variable is carbon (CO_2) emission (proxy for environmental quality). HD*GDP and $HD*GDP^2$ are the respective interaction terms in model 2 and 3 for assessing the moderating role of human development in the long-run. TO*GDP and $TO*GDP^2$ are the respective interaction terms in model 5 and 6 for evaluating the moderating role of trade openness in the long-run.

Source: Authors' calculation.

To validate these findings, the study employs the PMG-ARDL estimator, which accounts for short- and long-run effects, panel heterogeneity, and adjustment speed to equilibrium. The PMG results (Table 10) broadly confirm FMOLS outcomes, reaffirming the EKC hypothesis for BRICS (Shahbaz & Sinha, 2019; Mahmood et al., 2023). Both HD and TO increase emissions independently, but their interaction with GDP significantly lowers environmental degradation, highlighting the role of social advancement and globalization in moderating growth–environment linkages (Sinha & Sen, 2016; Shahbaz et al., 2021; Singh & Kanaujiya, 2025). Importantly, the error-correction term (ECT_{t-1}) is significantly negative, confirming a stable adjustment process towards long-run equilibrium and supporting the existence of dynamic interdependencies among growth, trade, human development, and emissions (Pao & Tsai, 2010).

Table 10. Robustness check using PMG-ARDL estimations

Independent Variable	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Long-run coefficients						
GDP	0.262[c] (0.009)	-0.412[b] (0.170)	0.634[b] (0.239)	1.552[c] (0.184)	3.299[c] (0.436)	1.180[c] (0.329)
GDP^2	0.002 (0.005)	0.055[c] (0.004)	0.187[c] (0.053)	-0.016[b] (0.008)	0.027[c] (0.006)	-1.190[c] (0.279)
HD	2.115[c] (0.182)	23.401[c] (6.049)	1.076 (1.761)	-	-	-
HD*GDP	-	-2.430[c] (0.716)	-	-	-	-
HD*GDP^2	-	-	0.385[c] (0.109)	-	-	-
TO	-	-	-	0.069 (0.065)	6.409[c] (1.171)	-3.464[c] (0.998)
TO*GDP	-	-	-	-	-0.725[c] (0.133)	-
TO*GDP^2	-	-	-	-	-	0.401[c] (0.094)
Convergence Coefficient (ECT_{t-1})	-0.181[b] (0.170)	-0.367[a] (0.187)	-0.345[b] (0.144)	-0.318[c] (0.118)	-0.213[a] (0.122)	-0.042[b] (0.020)
Short-run coefficients						
ΔGDP	1.139[c] (0.217)	1.776[a] (1.021)	1.042[a] (0.553)	0.371[c] (0.092)	0.496[c] (0.107)	0.491 (0.350)
ΔGDP^2	0.005 (0.006)	-0.011[a] (0.006)	0.454 (0.263)	0.006[a] (0.003)	-0.004a (0.002)	0.015 (0.506)
ΔHD	1.532[a] (0.800)	-17.535 (21.258)	-3.533 (7.044)	-	-	-
ΔHD*GDP	-	1.706 (2.536)	-	-	-	-
ΔHD*GDP^2	-	-	-0.035 (0.636)	-	-	-
ΔTO	-	-	-	0.084[a] (0.048)	-0.659 (0.416)	0.530 (1.850)
ΔTO*GDP	-	-	-	-	0.092[a] (0.052)	-
ΔTO*GDP^2	-	-	-	-	-	-0.014 (0.134)
Marginal Effects						
Minimum	-	0.481	3.291	-	-0.429	-1.157
Mean	-	3.126	6.336	-	0.360	2.014
Maximum	-	8.149	7.913	-	1.859	3.657

Note: 'a' significant at 10%, 'b' significant at 5%, and 'c' significant at 1% level of significance. Standard errors are in parenthesis. Dependent variable is carbon (CO_2) emission (proxy for environmental quality). HD*GDP and HD*GDP^2 are the respective interaction terms in model 2 and 3 for assessing the moderating role of human development in the long-run. TO*GDP and TO*GDP^2 are the respective interaction terms in model 5 and 6 for evaluating the moderating role of trade openness in the long-run.

Source: Authors' calculation.

4.4 Dumitrescu and Hurlin Granger Test of Panel Causality

The Dumitrescu–Hurlin (2012) panel causality test is well-suited for heterogeneous panels as it allows slope parameters and causal dynamics to vary across cross-sections, distinguishing between Homogeneous Non-Causality (HNC), Homogeneous Causality (HC), and Heterogeneous Causality (HEC). Unlike traditional Granger causality, it identifies causal effects present only in subsets of countries. Built on individual Wald statistics aggregated into robust test statistics, it accommodates cross-sectional dependence and non-stationarity—common in macro panels like BRICS—and can be integrated with second-generation unit root tests (Bai & Ng-PANIC, Pesaran CIPS). This makes it particularly effective for analyzing the growth–environment nexus, where growth, trade openness, and human development exert asymmetric influences on emissions.

Table 11 reports the Dumitrescu–Hurlin results for BRICS. The findings reveal strong bidirectional causality between GDP and CO_2 emissions, suggesting feedback mechanisms where economic expansion drives emissions while environmental constraints influence growth, consistent with Alam et al. (2016). Similarly, human development (HD) demonstrates homogeneous bidirectional causality with CO_2, indicating that welfare improvements and carbon dynamics are systematically linked across countries despite developmental heterogeneity. In contrast, trade openness (TO) shows unidirectional causality toward CO_2, implying that liberalization increases emissions without reciprocal effects, aligning with Sinha and Sen (2016).

Table 11. D-H Causality Test Results

Null Hypothesis (H_0)	W-Stat.	Zbar-Stat.	Prob.	Inference
GDP does not homogeneously cause CO_2	4.24	4.41	0.00	GDP ↔ CO2
CO_2 does not homogeneously cause GDP	8.03	9.68	0.00	
GDP^2 does not homogeneously cause CO_2	1.72	0.90	0.37	GDP^2 ⤚ CO2
CO_2 does not homogeneously cause GDP^2	1.84	1.07	0.29	
HD does not homogeneously cause CO^2	6.40	7.41	0.00	HD ↔ CO2
CO_2 does not homogeneously cause HD	4.82	5.22	0.00	
TO does not homogeneously cause CO_2	4.49	4.75	0.00	TO → CO2
CO_2 does not homogeneously cause TO	1.59	0.71	0.48	
HD*GDP does not homogeneously cause CO_2	6.41	7.42	0.00	HD*GDP ↔ CO2
CO_2 does not homogeneously cause HD*GDP	4.37	4.59	0.00	
HD*GDP^2 does not homogeneously cause CO_2	6.37	7.37	0.00	HD*GDP^2 ↔ CO2
CO_2 does not homogeneously cause HD*GDP^2	6.12	7.01	0.00	
TO*GDP does not homogeneously cause CO^2	5.09	5.59	0.00	TO*GDP → CO2
CO^2 does not homogeneously cause TO*GDP	2.17	1.52	0.13	
TO*GDP_2 does not homogeneously cause CO_2	1.38	0.43	0.67	TO*GDP^2 ⤚ CO2
CO_2 does not homogeneously cause TO*GDP^2	1.31	0.33	0.74	

Notes: '→' means unidirectional causality, '↔' stands for bidirectional causality, and '⤚' represents no causality.

Source: Authors' calculation.

Crucially, interaction terms (HD*GDP and HD*GDP^2) also display strong homogeneous bidirectional causality with CO_2, supporting Ehigiamusoe and Dogan (2022), who argue that growth moderated by social and environmental factors intensifies emissions. By contrast, TO*GDP and TO*GDP^2 reveal weak and insignificant causality, highlighting heterogeneous effects of trade–income linkages on emissions. Overall, these results confirm differentiated yet interdependent causal dynamics in BRICS, reinforcing the need for tailored but coordinated policy strategies.

4 CONCLUSION, RECOMMENDATIONS AND STUDY LIMITATIONS

This study explored the growth–environment nexus in BRICS economies by incorporating the moderating roles of trade openness and human development. The findings affirm the Environmental Kuznets Curve (EKC) hypothesis, consistent with Shahbaz and Sinha (2019), Mahmood et al. (2023), and Pao and Tsai (2010), showing that economic growth initially worsens emissions before transitioning towards sustainability as income rises. However, the results reveal that while trade openness and human development can independently intensify emissions, their interaction with economic growth helps mitigate environmental degradation, aligning with the insights of Sinha and Sen (2016), Ehigiamusoe and Dogan (2022), and Singh and Kanaujiya (2025). This underscores the dualistic role of social progress and globalization, which may initially exert environmental stress but gradually facilitate cleaner technologies, greater efficiency, and structural change across BRICS economies (Alam et al., 2016; Sebri & Ben-Salha, 2014).

From a policy standpoint, the results highlight the need for BRICS countries to adopt differentiated yet coordinated strategies. Expanding renewable energy adoption, incentivizing green technological innovation, and tightening environmental standards in trade agreements are crucial to balancing growth and sustainability (Chishti & Sinha, 2022; Sharif et al., 2025). Human development policies should integrate environmental education, energy efficiency, and social awareness to strengthen the capacity of populations to support low-carbon transitions (Sinha & Sen, 2016; Ma & Wang, 2021). Likewise, promoting green trade and political stability could enhance the effectiveness of international governance frameworks, reinforcing findings from Guo et al. (2025). A coordinated BRICS strategy combining economic integration with sustainability goals would not only lower carbon intensity but also position these economies as global leaders in green transition (Iwata et al., 2012).

Despite its contributions, the study has limitations. First, it employs aggregate panel data, which may obscure country-specific nuances such as institutional capacity and energy mix differences, a gap noted in previous literature (Alam et al., 2016; Sebri & Ben-Salha, 2014). Second, while FMOLS and PMG estimators are robust, they cannot fully capture structural breaks or asymmetric shocks from crises or technological disruptions, limiting generalizability

(Chishti & Sinha, 2022). Third, the study focuses on CO_2 emissions without including broader environmental indicators such as biodiversity loss or particulate pollution, which could provide a more comprehensive picture of environmental degradation (Iwata et al., 2012). Future research should integrate micro-level data, adopt nonlinear and asymmetric approaches, and explore institutional and political economy dimensions to better assess the sustainability trajectory of BRICS economies (Guo et al., 2025; Sharif et al., 2025).

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