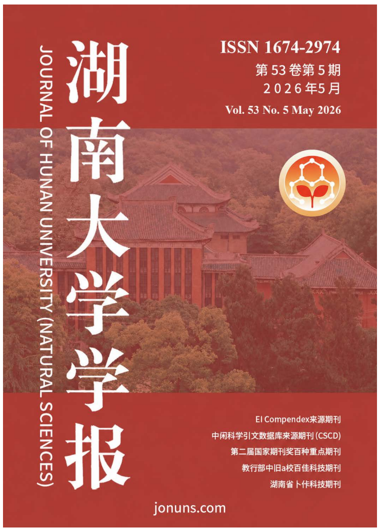

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Green Growth, Green Technological Innovation, and Environmental Sustainability: Evidence from BRICS Economies

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Abstract: This study investigates the effects of green growth (GG) and green technological innovation (GTI) on environmental degradation, measured by per-capita CO_2 emissions (LED), across the BRICS economies (Brazil, Russia, India, China, and South Africa) over the period 1990–2023. Motivated by the urgent need to balance fast-paced economic development with sustainable ecology in high-growth emerging economies, presents three key innovations: (i) the analysis of GG and GTI is conducted concurrently with the EKC dynamics in the context of the integrated PMG-ARDL approach; (ii) a newer dataset (1990–2023) compared to previous studies focusing on BRICS countries; and (iii) cross-sectional dependence tests and model robustness verification through Panel DOLS and FMOLS. Unit root testing shows mixed order of integration between I(0) and I(1), which fulfills PMG-ARDL requirements, while Kao residual co-integration test confirms the existence of long-term equilibrium among variables. The long-run estimation results show that GG and GTI have a significant impact on lowering CO_2 emissions by 0.38% and 0.65% per unit increase, respectively, which supports the Porter Hypothesis and decoupling paradigm. FDI also has a significant impact on lowering emissions (0.32%), which aligns with the Pollution Halo Hypothesis. Contrarily, fossil fuel use and population expansion contribute to worsening environmental quality. More importantly, the significant positive value of GDP and the negative value of GDP^2 validate the EKC hypothesis in BRICS.The error-correction term (−0.680) indicates that 68% of short-run deviations are corrected per period. Granger-causality tests reveal unidirectional causality from GG and GTI to LED, and bidirectional causality among GDP, FDI, fossil fuels, population growth, and LED. These findings advocate for coordinated policy frameworks that prioritise green technology investment, renewable energy transition, and carbon pricing across BRICS member states to attain Sustainable Development.

Keywords: green growth; green technological innovation; environmental degradation; PMG-ARDL; environmental kuznets curve; BRICS; decoupling.

车辆撞击作用下钢筋混凝土桥墩动力响应研究：基于杜哈梅尔积分的单自由度分析与参数评估

摘要：

本研究考察了1990—2023年期间金砖国家经济体（巴西、俄罗斯、印度、中国和南非）中绿色增长（GG）和绿色技术创新（GTI）对环境退化的影响，其中环境退化以人均二氧化碳排放量（LED）衡量。鉴于高增长新兴经济体亟需在快速经济发展与生态可持续性之间实现平衡，本文提出了三项主要创新：（i）在综合PMG-ARDL方法框架下，将绿色增长和绿色技术创新与环境库兹涅茨曲线（EKC）动态同时进行分析；（ii）相较于以往关注金砖国家的研究，本文采用了更新的数据集 (1990—2023年)；（iii）通过横截面依赖性检验以及Panel DOLS和FMOLS方法进行模型稳健性验证。单位根检验结果显示，各变量的单整阶数混合分布于I(0)和I(1)之间，符合PMG-ARDL方法的适用要求；Kao残差协整检验则证实变量之间存在长期均衡关系。长期估计结果表明，绿色增长和绿色技术创新对降低二氧化碳排放具有显著影响，每单位增加分别可使排放降低0.38%和0.65%，这支持了波特假说和脱钩范式。外国直接投资（FDI）也对降低排放具有显著影响（0.32%），这与污染光环假说相一致。相反，化石燃料使用和人口增长会加剧环境质量恶化。更重要的是，GDP的显著正值和GDP^2的负值验证了金砖国家中的环境库兹涅茨曲线假说。误差修正项（−0.680）表明，每期约68%的短期偏离会得到修正。格兰杰因果检验显示，绿色增长和绿色技术创新对LED存在单向因果关系，而GDP、FDI、化石燃料、人口增长与LED之间存在双向因果关系。研究结果主张金砖国家成员应建立协调一致的政策框架，优先推动绿色技术投资、可再生能源转型和碳定价机制，以实现可持续发展。

关键词：

绿色增长；绿色技术创新；环境退化；PMG-ARDL；环境库兹涅茨曲线；金砖国家；脱钩

1. Introduction

Climate change represents one of the most pressing threats to global ecological sustainability, producing cascading consequences for both ecosystems and human welfare [12, 13]. Its manifestations rising sea levels, prolonged droughts, intensified tropical cyclones, and widespread pollution arise primarily from anthropogenic greenhouse gas emissions driven by the combustion of fossil fuels [2, 8]. The nexus between CO_2 emissions and economic development has consequently attracted sustained scholarly attention, particularly for emerging economies that face simultaneous pressures for rapid industrialisation and environmental stewardship [13, 35].

The concept of green growth has evolved as an innovative strategy that aims at balancing growth and development with sustainability. Green growth can be defined as a strategy adopted by UNESCAP and implemented by the OECD [31] that advocates for low carbon, resource-efficient, and inclusive growth. Green growth has been categorised into three aspects which include (i) inclusiveness – equal provision of sustainable resources and clean energy to all; (ii) low-carbon growth reduced emissions of greenhouse gases; and (iii) resource efficiency reduced depletion of natural resources [14]. Along with green growth, GTI plays a significant role in reducing emissions.

The BRICS economies (Brazil, Russia, India, China, and South Africa) constitute a particularly pertinent context for such research. Collectively, these countries contribute 37.3% to global GDP [13] and are notable for fast-paced industrialization, extensive fossil fuel dependency, and intense environmental stress. Although their political and institutional regimes vary greatly, all five BRICS member states have established green transition aspirations [18]. Nevertheless, scientific knowledge of the practical effectiveness of green growth strategies in the environmental performance of BRICS countries is rather sparse, especially for extended time periods that capture the post-2015 Sustainable Development Goal era.

The current study bridges this information gap by investigating the impact of GG and GTI on environmental pollution proxied by log per capita CO_2 emissions in BRICS countries between 1990 and 2023. The expanded sample period allows researchers to identify both the initial formation of green policies and subsequent transitions with greater accuracy. We adopt a novel approach based on the PMG-ARDL estimator that explicitly considers mixed-order integration (I(0)/I(1)) established through unit root testing and cross-sectional dependence across the panel. Robustness is assessed via Panel DOLS and FMOLS. The study further tests the Environmental Kuznets Curve (EKC) hypothesis and examines Granger-causal linkages among all variables.

The paper contributes uniquely to existing knowledge on the topic by making three key innovations. First, the current study jointly evaluates the emission-reduction potential of GG and GTI through a unified econometric model, in contrast with previous research that considers the two concepts independently. Second, the current study uses a more extensive and up-to-date panel data set (1990–2023) compared to other BRICS-related studies. Finally, cross-sectional dependence tests and various sensitivity analyses are performed for greater inferential power.

The study aims to answer the following questions:

RQ1: What contribution does green growth make to alleviating environmental degradation in BRICS countries?

RQ2: What is the contribution of green technological innovation to lowering carbon dioxide emissions in BRICS countries?

The rest of this paper is structured as follows. Section 2 presents an overview of the literature. The theoretical framework is discussed in Section 3. The description of the data and empirical model is provided in Section 4. Results and discussion are presented in Section 5. Section 6 offers some concluding remarks.

Figure 1. Conceptual Framework of Green Growth (Authors' elaboration based on [31])

2. Literature Review

2.1 Green Growth and Environmental Degradation

The link between green growth and environmental quality has been a core issue within ecological economics literature. According to Jackson [22], there is a notion that growth may be realized even when there is no continuous use of resources; a principle on which the entire concept of green growth is founded. In reality, the demand side emissions approach by Wiebe and Yamano [36] proves that for green growth to succeed, it must incorporate changes in the supply chain and environmentally sound production processes.

The sustainable development theory [11] highlights the co-relation among three pillars: economic, social, and environmental, which help in formulating policies for green growth based on evidence. There is an increasing trend of empirical evidence showing that green growth lowers CO_2 emission levels for both advanced and developing nations [9, 18, 20]. The use of various econometric techniques in previous literature supports the finding that there exists an inverse correlation between green growth and greenhouse gas emission levels.

H1: Green growth is negatively associated with CO_2 emissions (environmental degradation).

2.2 Green Technological Innovation and Environmental Degradation

Environmental technological innovation has been widely acknowledged as an important approach for attaining environmental sustainability. According to previous research, innovation in environmental technologies can reduce emissions from human activities because they improve production efficiency and replace fossil fuels with green energy sources [32]. Further research findings reveal that innovation contributes greatly to reducing ecological impacts in times of structural change and also assists in ecological restoration using innovative technology [7, 27, 37].

In the context of BRICS and other emerging economies, it has been observed that technological innovation helps in decreasing ecological impacts and contributes to improving environmental sustainability [1, 19, 26, 30]. In addition, other empirical studies show that both green and digital technology innovations assist in making lower carbon transitions and thus contribute immensely to environmental sustainability [7, 19, 26].

H2: Green technological innovation is negatively associated with CO_2 emissions.

3. Theoretical Framework

The theoretical framework underpinning the study draws from five interrelated theories that will help explain why certain variables have been chosen, hypotheses posed, and relationships proposed.

According to Sustainable Development Theory [15], advanced by the Brundtland Commission, economic goals and environmental protection are not mutually exclusive. Green growth as a policy tool aims at promoting economic growth while lowering consumption and minimizing environmental damage [15]. This theory explains why GG is included as an important determinant of CO_2 emissions.

The second theory used in this study is Natural Capital Theory, which holds that the environment is productive for the economy and ecology [10]. Green growth relies on the preservation of natural capital stocks achieved through renewable energy deployment, efficient use of resources, and GTI [6]. This theory explains why there exists a relationship between the FF variable and sustainability.

The last theory, the Porter hypothesis [34], states that properly designed environmental regulations foster innovation and may improve a country's competitive advantage. In the context of this research, the theory implies that good green regulation fosters GTI, which leads to lower emissions as indicated by the predicted negative GTI coefficient in H2.

Relative decoupling means that the rate of economic production increases more rapidly than the environmental effect, while absolute decoupling implies no correlation at all. Figure 2 depicts the decoupling mechanism. The inclusion of GG and GTI in the regression model empirically evaluates whether the BRICS countries have been experiencing productivity-based decoupling of emissions and growth.

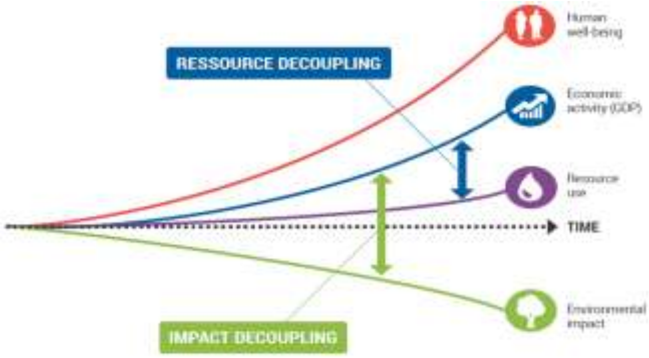


Figure 2. The Decoupling of Economic Growth from Environmental Degradation (Authors' elaboration based on [23])

The EKC hypothesis [17] suggests that the effect of income on pollution follows an inverted U-shaped pattern. Beyond a certain income level, increases in technological capacity, institution strength, and consumer preference for environmental amenities lead to lower levels of emissions. This assumption is reflected in the use of GDP and GDP^2 in the regression equation.

Figure 3 shows the theoretical basis for this study, showing how GG, GTI, GDP (EKC), FDI, FF, and POP impact environmental performance.

Figure 3. Conceptual Framework of the Study (Authors' elaboration)

4. Data, Model, and Estimation Methods

4.1 Data and Variable Description

This study uses a balanced panel dataset for the five BRICS economies (Brazil, Russia, India, China, South Africa) spanning the period 1990–2023 ($N = 5$; $T = 34$; total observations = 170). The study period

(1990–2023) is selected for three key reasons: (i) it captures the baseline pre-Rio Earth Summit period (1992) and all subsequent international environmental agreements, including the Kyoto Protocol, the Paris Agreement, and the 2030 Agenda for Sustainable Development; (ii) it encompasses the rapid industrialisation phase of China and India alongside the post-Soviet transition of Russia; and (iii) it allows estimation of reliable long-run dynamics within the PMG-ARDL framework. The variables are obtained from the World Development Indicators (WDI), the OECD database, and the World Intellectual Property Organization (WIPO) database. Table 1 summarises variable descriptions, units, and sources.

Table 1. Variable Descriptions, Measurement Units, and Sources

No.	Variable	Symbol	Measurement Unit	Source
1	Log of Environmental Degradation	LED	Log of CO_2 Emissions per Capita (metric tons)	WDI
2	Green Growth	GG	Environmentally Adjusted Multifactor Productivity Growth (index)	OECD
3	Green Technological Innovation	GTI	Log of Total Patent Applications: Residents + Non-Residents	WIPO
4	Gross Domestic Product	GDP	Annual Growth Rate (%)	WDI
5	GDP Squared	GDP^2	Square of Annual GDP Growth Rate	WDI
6	Foreign Direct Investment	FDI	Net Inflows (% of GDP)	WDI
7	Fossil Fuel Consumption	FF	% of Total Final Energy Consumption	WDI
8	Population Growth	POP	Annual Growth Rate (%)	WDI

Source: Authors' elaboration. WDI = World Development Indicators; OECD = Organisation for Economic Co-operation and Development; WIPO = World Intellectual Property Organization.

4.2 Empirical Model Specification

Following the literature on environmental economics and green growth [20, 18, 30], the baseline panel log-linear model is specified as:

$$LED_{it} = \beta_0 + \beta_1 GG_{it} + \beta_2 GTI_{it} + \beta_3 GDP_{it} + \beta_4 GDP_{it}^2 + \beta_5 FDI_{it} + \beta_6 FF_{it} + \beta_7 POP_{it} + \varepsilon_{it}$$

(1)

where subscripts i (i = 1 to 5) and t (t = 1990 to 2023) index country and year respectively; β_0 is the intercept; β_1–β_7 are the long-run elasticity coefficients; and ε_{it} is the idiosyncratic error term. All continuous variables except GG and the growth-rate variables are expressed in natural logarithms to interpret coefficients as elasticities.

Based on established theoretical priors and the reviewed literature, the following directional hypotheses are formulated: H1 ($\beta_1 < 0$): green growth reduces CO_2 emissions; H2 ($\beta_2 < 0$): GTI reduces CO_2 emissions; H3 ($\beta_3 > 0$, $\beta_4 < 0$): EKC hypothesis holds for BRICS; H4 ($\beta_5 < 0$): FDI supports the Pollution Halo Hypothesis; H5 ($\beta_6 > 0$): fossil fuel consumption raises emissions; H6 ($\beta_7 > 0$): population growth exacerbates environmental degradation.

4.3 Estimation Methodology

4.3.1 Cross-Sectional Dependence Testing

In panels with common global shocks (e.g., oil price crises, the 2008 global financial crisis, the COVID-19 pandemic), cross-sectional dependence (CSD) among panel units is likely. Failing to account for CSD produces size-distorted test statistics and biased long-run estimates. This study applies the Breusch-Pagan LM test, Pesaran Scaled LM test, and Pesaran CD test to detect CSD prior to unit-root and cointegration testing.

4.3.2 Panel Unit-Root Analysis

The stationarity properties of all variables are assessed using the Augmented Dickey-Fuller (ADF) Fisher Chi-square test and the Phillips-Perron (PP) Fisher Chi-square test [28, 21]. For each test, the null hypothesis H_0 states that the panel contains a unit root (non-stationarity), and H_0 is rejected when the p-value falls below the selected significance thresholds of 1%, 5%, or 10%. Lag lengths are selected automatically via the Schwarz Information Criterion (SIC). The mixed integration order I(0)/I(1) confirmed in the results satisfies the necessary precondition for PMG-ARDL estimation.

4.3.3 PMG-ARDL Estimation

The main technique employed here is the PMG-ARDL approach introduced by Pesaran [33]. The use of PMG-ARDL model has three main advantages in the context of the current analysis: (i) it can incorporate variables that are integrated of order I(0) and I(1), thereby eliminating the stationarity testing step prior to analysis; (ii) it can handle small-to-moderate panels where there exist heterogeneous short-run dynamics but homogeneous long-run relationships; and (iii) it corrects for any possible problems of autocorrelation, endogeneity, and heterogeneity using ECM [5, 29].

The generic ARDL (p, q_1, q_2, …) model is:

$$\Delta LED_{it} = \alpha_i\left(LED_{i,t-1} - \boldsymbol{\theta}'\mathbf{X}_{it}\right) + \sum_{j=0}^{p-1} \gamma_{ij}\, \Delta\mathbf{X}_{i,t-j} + u_{it}$$

(2)

where α_i represents the speed-of-adjustment coefficient that needs to be negative and statistically significant for validating the process of cointegration and convergence towards the long-run equilibrium state; θ_i refers to the vector of long-run regression coefficients (restricted to homogeneity across i in the pooled equation framework); X_{it} represents the vector of regressors; γ_{ij} is related to short-run dynamics that differ between equations; and u_{it} represents the disturbance term. Selection of lag length is done based on the Akaike Information Criterion (AIC).

$$\mathbf{X}_{it} = \begin{pmatrix} GG_{it} \\ GTI_{it} \\ GDP_{it} \\ GDP_{it}^2 \\ FDI_{it} \\ FF_{it} \\ POP_{it} \end{pmatrix}$$

(3)

4.3.4 Granger Causality Testing

To identify the causal relationships among the variables, the Granger causality approach [16] is employed using a lag length of two, determined by the Akaike Information Criterion (AIC). This method evaluates the null hypothesis that one variable does not predict another; rejecting this hypothesis indicates that historical values of the explanatory variable provide meaningful information for forecasting the dependent variable. Outcomes may indicate unidirectional causality (X → Y or Y → X), bidirectional causality (X ⇔ Y), or no causal relationship. These findings carry direct policy implications regarding the sequencing of green interventions.

4.3.5 Diagnostic and Robustness Testing

Model validity will be evaluated based on four criteria: (i) Breusch-Godfrey Serial Correlation LM Test for detecting any autocorrelations; (ii) Breusch-Pagan-Godfrey Test for detecting any heteroskedasticity; (iii) Ramsey Reset Test to detect any misspecification of model function; (iv) Stability test, namely CUSUM and CUSUMSQ for each individual country. The robustness of the long-run estimators will be analyzed via Panel DOLS and FMOLS estimation models. These estimators' control for any endogeneity and serial correlation [33].

5. Results and Discussion

5.1 Descriptive Statistics

Descriptive statistics for all variables are presented in Table 2. The range for LED is from −0.365 to 2.801 (average = 1.412). This suggests that there is significant variation in the level of per-capita carbon dioxide emissions among BRICS countries. The range for GG is from −6.519 to 12.390 (average = 2.104). GTI is defined as the logarithm of the total number of patents applied for and has a range of 0.003 to 1.772 (average = 0.128). GDP growth spans −14.531 to 14.230% (mean: 3.986%). FDI averages 1.996% of GDP, while FF averages 77.18%, underscoring persistent fossil fuel dependence across the group. LED, FF, and POP are negatively skewed; GG, GTI, GDP^2, and FDI are positively skewed. The high kurtosis of GTI (14.369) indicates extreme outliers attributable to China's dominant patent activity.

Table 2. Descriptive Statistics of Key Variables

Statistic	LED	GG	GTI	GDP	GDP²	FDI	FF	POP
Mean	1.4115	2.1042	0.1275	3.9856	37.826	1.9958	77.183	0.9224
Median	1.7072	2.2559	0.0248	4.2618	22.976	1.7285	84.724	0.9849
Maximum	2.8012	12.390	1.7719	14.230	211.15	9.6602	96.005	2.7813
Minimum	−0.365	−6.519	0.0031	−14.531	0.0158	−1.756	51.215	−0.460
Std. Dev.	0.9091	2.9705	0.3447	4.6979	42.947	1.5862	14.234	0.6965
Skewness	−0.230	0.217	3.526	−0.791	1.911	1.013	−0.571	−0.110
Kurtosis	1.664	3.405	14.369	4.604	7.101	5.164	1.742	2.379
Obs.	170	170	170	170	170	170	170	170

Source: Authors' calculations. All figures rounded to four decimal places.

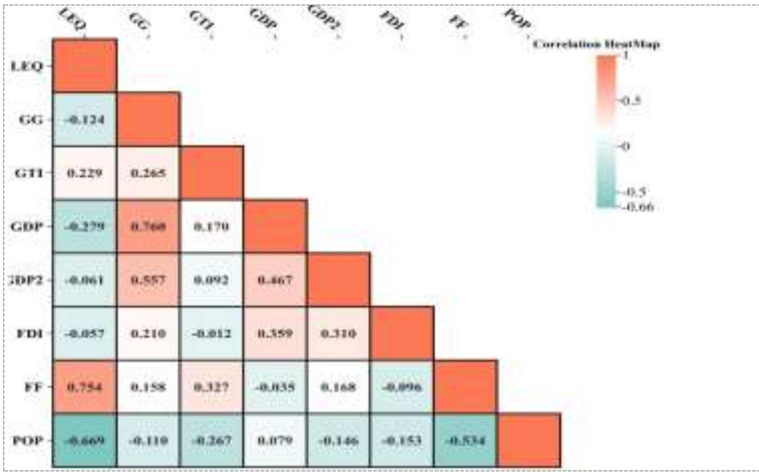


Figure 4. Correlation Heatmap of Study Variables (Authors' calculations)

5.2 Cross-Sectional Dependence Test

Table 3 reports the results of the cross-sectional dependence tests. The findings from all three tests indicate rejection of the null hypothesis of no cross-sectional dependence at the 1% and 5% significance levels. These findings confirm that BRICS economies are subject to common shocks and interdependencies a finding consistent with their integrated commodity and financial markets. Accordingly, second-generation panel methods that account for CSD (ADF-Fisher, PP-Fisher, PMG-ARDL) are appropriate for this dataset.

Table 3. Cross-Sectional Dependence Test Results

Test	Statistic	d.f.	p-Value
Breusch-Pagan LM	20.9756	10	0.0213**
Pesaran Scaled LM	1.3362		0.0185**
Pesaran CD	3.1014		0.0019*

Source: Authors' calculations. Note: *p < 0.01; **p < 0.05.

5.3 Panel Unit-Root Analysis

Table 4 reports ADF-Fisher and PP-Fisher unit-root test results. GG, GDP, GDP², and FDI are stationary at the level I(0). In contrast, LED, GTI, FF, and POP achieve stationarity only at the first difference I(1). The unit root null hypothesis is rejected for all variables, indicating that they are stationary at their respective levels of integration at 1% or 5% significance at the appropriate integration order. This mixed I(0)/I(1) order satisfies the prerequisite for PMG-ARDL estimation and renders standard cointegration tests (Johansen) inapplicable.

Table 4. Panel Unit-Root Test Results (ADF-Fisher and PP-Fisher)

Variable	ADF Level I(0)	ADF First Diff. I(1)	PP Level I(0)	PP First Diff. I(1)	Order
LED	10.436 (0.403)	31.162* (0.001)	8.375 (0.592)	67.616* (0.000)	I(1)
GG	42.845* (0.000)	108.64* (0.000)	61.660* (0.000)	154.34* (0.000)	I(0)
GTI	9.748 (0.463)	32.326* (0.000)	11.952 (0.288)	58.593* (0.000)	I(1)
GDP	31.179* (0.001)	104.33* (0.000)	59.083* (0.000)	160.48* (0.000)	I(0)
GDP²	40.648* (0.000)	116.45* (0.000)	57.080* (0.000)	147.21* (0.000)	I(0)
FDI	20.621** (0.024)	71.089* (0.000)	29.512* (0.001)	110.77* (0.000)	I(0)
FF	7.372 (0.690)	63.278* (0.000)	8.132 (0.616)	111.18* (0.000)	I(1)
POP	12.724 (0.240)	63.120* (0.000)	13.329 (0.206)	42.484* (0.000)	I(1)

Source: Authors' calculations. Note: *p < 0.01; **p < 0.05. T&I = Trend and Intercept specification; intercept-only results reported for brevity. p-values in parentheses.

5.4 PMG-ARDL Estimation Results

5.4.1 Long-Run Estimates

Table 5 presents the long-run estimates from the PMG-ARDL model. The Kao residual cointegration test confirms cointegration among the variables (t-statistic: −1.785; p = 0.037), validating the long-run equilibrium relationship assumed by the PMG-ARDL framework.

Green Growth (GG): The long-run coefficient of GG is negative and statistically significant at the 5% level (β = −0.380; p = 0.036), indicating that a one-unit increase in the environmentally adjusted multifactor productivity index leads to a 0.38% decline in per-capita CO_2 emissions, thereby supporting the proposed hypothesis. H1. This result is economically meaningful: GG reduces emissions through three channels. First, green growth drives investment in renewable energy and clean technologies, directly substituting fossil-fuel-intensive production. Secondly, renewable energy deployment can lead to significant reductions in carbon emissions globally, according to IRENA. Third, improvements in energy efficiency for transportation, building, and household appliances have an emissions reduction effect. These findings corroborate earlier research [9, 18, 20].

Green Technological Innovation (GTI): GTI shows negative and marginally significant coefficient (β = -0.651; p = 0.058), confirming H2. One unit of GTI lowers CO_2 emissions by around 0.65%. This observation reflects the critical contribution of renewable energy technology (solar energy, wind power, carbon sequestration technology) along with efficient home appliances, electric vehicles, and green building materials to decrease dependence on fossil fuels. It should be noted that GTI appears to be a more effective method of reducing CO_2 emissions compared to GG due to its slightly higher magnitude despite the marginally significant coefficient. The finding confirms other existing research studies [7, 30, 32].

GDP and GDP² EKC Hypothesis: GDP exhibits a significantly positive long-run coefficient (β = 0.474; p = 0.042), while GDP² is significantly negative (β = −0.275; p = 0.030). This inverted-U pattern confirms the Environmental Kuznets Curve hypothesis for BRICS economies: in the early stages of economic development, industrialisation and urbanisation increase emissions, but beyond an income threshold, structural transformation towards service-oriented economies and stricter environmental governance reduce emissions. Although GDP is measured as annual growth rate rather than income level, the nonlinear sign pattern is nonetheless consistent with EKC dynamics, as documented for BRICS by prior studies [17]. The results obtained in the above robustness checks are consistent throughout the study.

Foreign Direct Investment (FDI): FDI has a significant negative impact on the long-run relationship between CO_2 emissions (β = -0.324; p = 0.041). Thus, the Pollution Halo Hypothesis (PHH) is proven and H4 supported. Foreign investments into BRICS countries' economies bring better environmental technologies and higher environmental standards, which improve the overall environment in host countries. The findings confirm [25].

Fossil Fuel Consumption (FF): The variable FF has a positive and marginally significant relationship with CO_2 emissions (β = 0.162; p = 0.071) and confirms H5. Though the statistical significance of the relationship is low (significant at the 10% level), the theoretically correct positive direction and economic importance remain. The marginal increase in fossil fuel share leads to approximately 0.16% increment in CO_2 emissions. The result needs to be interpreted carefully as the coefficient can be considered too low due to relatively narrow variation in FF during the BRICS sample period.

Population Growth (POP): POP increases positively and marginally significantly CO_2 emissions ($\beta = 0.610$; $p = 0.094$), confirming H6. The 10% significance warrants noting, though the direction is firmly consistent with prior evidence and theoretical expectation.

Table 5. Long-Run PMG-ARDL Estimates

Variable	Coefficient	Std. Error	p-Value	Significance
GG	−0.3795	0.4860	0.0364	**
GTI	−0.6511	0.8752	0.0583	***
GDP	0.4735	0.6137	0.0418	**
GDP^2	−0.2754	0.0080	0.0304	**
FDI	−0.3244	0.4192	0.0405	**
FF	0.1623	0.0556	0.0708	***
POP	0.6104	0.3615	0.0939	***

Source: Authors' calculations. Dependent variable: LED (log per-capita CO_2 emissions). Significance: *$p < 0.01$; **$p < 0.05$; ***$p < 0.10$. Cointegration confirmed by Kao residual test ($t = -1.785$; $p = 0.037$).

5.4.2 Short-Run Dynamics and Error Correction

The short-run error correction estimates have been presented in Table 6. The value of the error correction coefficient is negative (−0.680) and statistically significant at the 1% level ($p < 0.001$). This reflects the high tendency to move towards the long-run equilibrium position, thereby showing that there exists a stable long-run equilibrium relationship. Economically speaking, it could be seen that any deviation of 68.03% from the long-run equilibrium position is adjusted within one period. Therefore, the rate of adjustment is relatively quick.

Short-run values such as ΔGG, ΔGTI, and ΔGDP have positive signs, while ΔGDP^2 and ΔFDI have negative signs. In the case of short-run values, there are differences with regard to signs between the long-run value because of the heterogeneity of short-run adjustments in the PMG-ARDL approach. For example, a positive value for ΔGG in the short run can be attributed to adjustment costs in the industrial sector due to green productivity growth.

Table 6. Short-Run PMG-ARDL Error-Correction Estimates

Variable	Coefficient	Std. Error	p-Value	Significance
CointEq01	−0.6803	0.0043	0.0000	*
Δ(GG)	0.0024	0.0022	0.0674	***
Δ(GTI)	3.4146	1.4906	0.0237	**
Δ(GDP)	0.0027	0.0017	0.0133	**
$\Delta(GDP^2)$	−0.0003	0.0002	0.0772	***
Δ(FDI)	−0.0013	0.0036	0.0212	**
Δ(FF)	0.0143	0.0040	0.0006	*
Δ(POP)	0.0228	0.0234	0.0332	**
Constant	−0.0071	0.0104	0.0967	***

Source: Authors' calculations. Dependent variable: ΔLED. *$p < 0.01$; **$p < 0.05$; ***$p < 0.10$. CointEq01 is the error-correction term; its negative and significant value confirms convergence to long-run equilibrium.

5.5 Robustness Checks: Panel DOLS and FMOLS

Panel DOLS and FMOLS estimation results are shown in Table 7. The findings for these approaches support the findings obtained through the PMG-ARDL approach. The variables GG, GTI, and FDI have negative signs, which are significant in both estimations, while the variables FF and POP have positive coefficients, which are also significant. The results in Table 7 again show that the EKC model follows a pattern where GDP has a positive effect on emission, while the quadratic effect GDP^2 shows negative effects. These findings across three different approaches reinforce the robustness of baseline results.

Table 7. Robustness Checks: Panel DOLS and FMOLS Estimates

V	DOL	DOL	FMOLS	FMOLS p
G	−0.41	0.013	−0.3109	0.0000*
G	−0.55	0.000	−0.4904	0.0348**
G	0.369	0.097	0.4601	0.0000*
G	−0.21	0.045	−0.2683	0.0116**
F	−0.28	0.005	−0.3924	0.0001*
F	0.172	0.000	0.1794	0.0495**
P	0.655	0.000	0.5604	0.0130**
L	1.028	0.000	1.0285	0.0000*

Source: Authors' calculations. Dependent variable: LED. *$p < 0.01$; **$p < 0.05$; ***$p < 0.10$.

5.6 Granger Causality Analysis

Table 8 shows the results of Granger causality test (lag order = 2, AIC selected). The test assesses the predictive precedence: X Granger-causes Y if past value of X is significant for predicting future value of Y, given past value of Y. The test is explained by considering policies: unidirectional causality means that policies designed to change the cause will have an effect, while policies on the consequence will have no impact; bidirectional causality indicates that there are feedbacks.

GG and GTI display unidirectional Granger causality towards LED (GG → LED, GTI → LED), although the reverse causations are insignificant. There is a clear policy implication in the finding: green growth and green technological investment may be applied as policy levers to bring down emissions without inducing any feedback from the emissions level back into the incentive for innovation. In other words, policy measures on GG and GTI will effectively lead to emissions reduction.

GDP, FDI, FF, and POP all show bidirectional causality with LED. For example, higher emissions (LED) may signal energy-intensive growth phases that attract or deter FDI, creating a feedback loop. The absence of any causal relationship between GDP^2 and LED in either direction is noteworthy: it suggests that the nonlinear income–emissions relationship embedded in EKC is a long-run equilibrium phenomenon rather than a short-run predictive one.

Table 8. Granger Causality (Predictive Influence) Test Results

Null Hypothesis (H_0)	Obs	F-St	p-Val	Resu	Causality
GG ↛ LED	160	5.15	0.1168	Supp	Unidirectional
LED ↛ GG	160	1.11	0.0297	Rejec	GG → LED
GTI ↛ LED	160	1.11	0.3222	Supp	Unidirectional
LED ↛ GTI	160	0.71	0.0415	Rejec	GTI → LED
GDP ↛ LED	160	7.41	0.0008	Rejec	Bidirectional
LED ↛ GDP	160	1.96	0.0432	Rejec	GDP ⇔ LED
GDP^2 ↛ LED	160	2.57	0.7193	Supp	No Causal
LED ↛ GDP^2	160	0.43	0.6484	Supp	Relationship
FDI ↛ LED	160	0.67	0.0092	Rejec	Bidirectional
LED ↛ FDI	160	0.61	0.0439	Rejec	FDI ⇔ LED
FF ↛ LED	160	2.68	0.0713	Rejec	Bidirectional
LED ↛ FF	160	10.5	0.0541	Rejec	FF ⇔ LED
POP ↛ LED	160	2.12	0.0227	Rejec	Bidirectional
LED ↛ POP	160	2.70	0.0703	Rejec	POP ⇔ LED

Source: Authors' calculations. Lag order = 2 (AIC-selected). ↛ denotes 'does not Granger-cause'. *$p < 0.01$; **$p < 0.05$; ***$p < 0.10$.

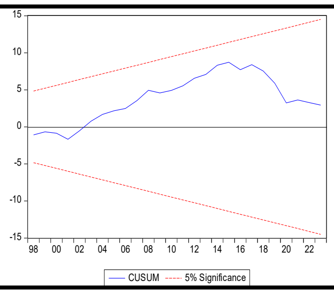
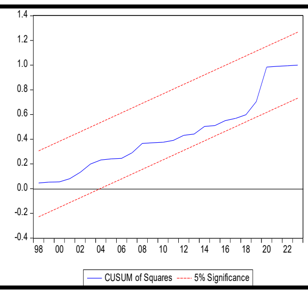
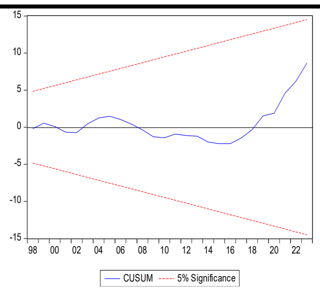
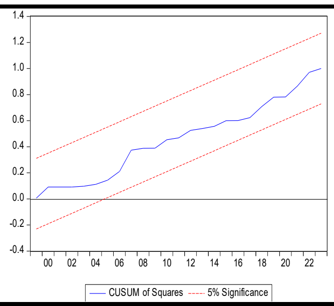
5.7 Diagnostic Tests

Table 9 summarises the diagnostic test outcomes. The serial correlation LM test (F = 0.081; p = 0.923) and the Breusch-Pagan-Godfrey heteroskedasticity test (F = 3.475; p = 0.490) fail to reject their respective null hypotheses, confirming the absence of serial correlation and the presence of homoskedastic residuals. The Ramsey RESET test (F = 0.039; p = 0.844) does not reject the null of correct functional form, validating the model specification. The Kao cointegration test (t = −1.785; p = 0.037) rejects the null of no cointegration. CUSUM and CUSUMSQ stability plots for all five countries confirm that estimated parameters remain within the 5% critical bounds throughout the sample period, indicating structural stability.

Table 9. Diagnostic Test Results

No.	Test	Statistic	p-Value	Conclusion
1	**Serial Correlation LM**	F = 0.0807	0.9225	No serial correlation
2	**Breusch-Pagan-Godfrey**	F = 3.4754	0.4896	No heteroskedasticity
3	**Kao Cointegration**	t = −1.7849	0.0371**	Variables cointegrated
4	**Ramsey RESET**	F = 0.0391	0.8436	Model correctly specified
5	**CUSUM / CUSUMSQ**			Stable (all within bounds)

Source: Authors' calculations. **$p < 0.05$.

Plot of CUSUM	Plot of CUSUMSQ
Brazil	Brazil
	
Russia	Russia
	
India	India

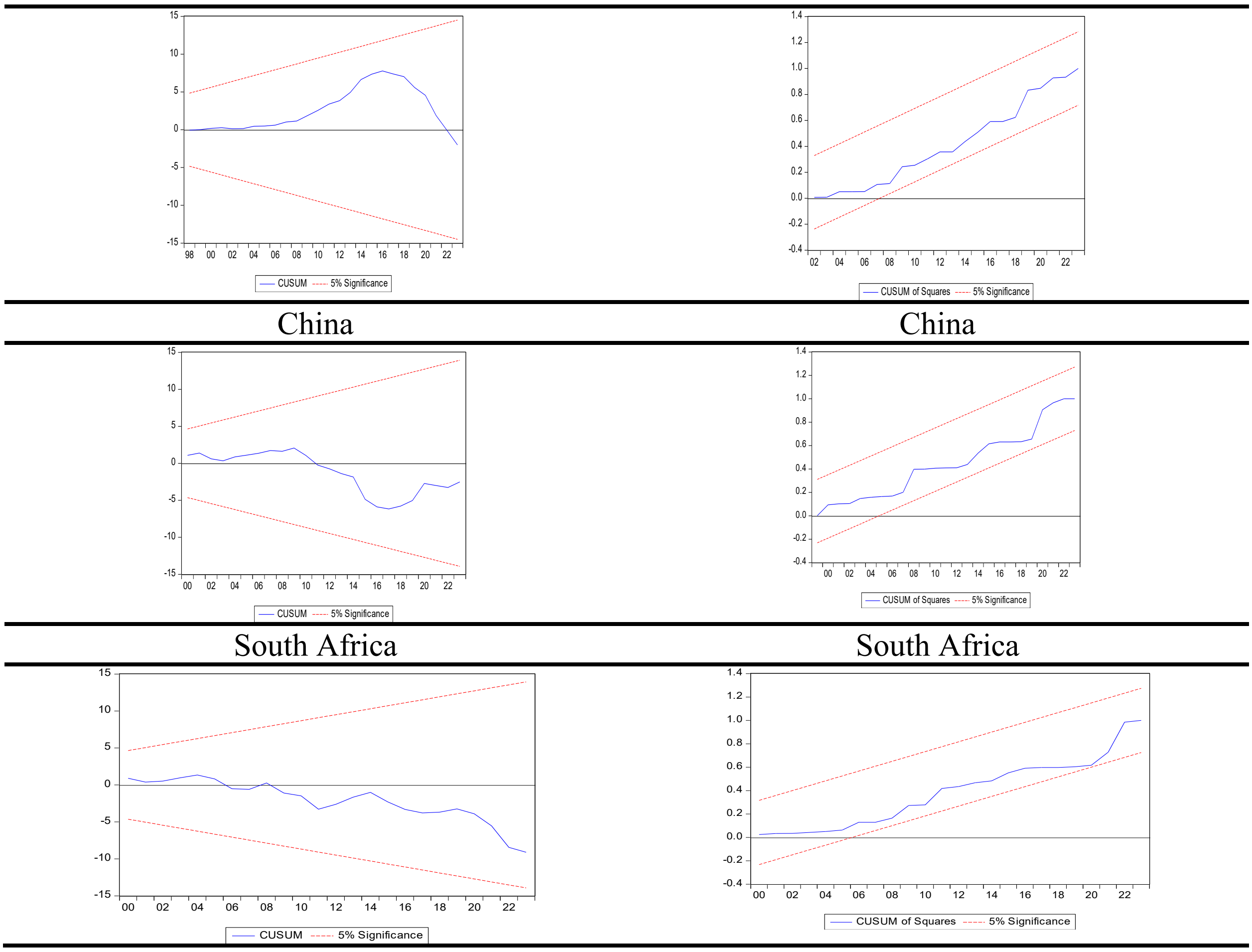


Figure 5. CUSUM and CUSUMSQ Stability Plots by Country (Brazil, Russia, India, China, South Africa) (Authors' calculations)

6. Conclusions, Policy Implications, and Future Directions

6.1 Conclusions

This study observed the long run and short run effects of green growth (GG) and green technological innovation (GTI) on environmental degradation, proxied by log per-capita CO_2 emissions, across the BRICS economies from 1990 to 2023. Using the PMG-ARDL approach with tests for cross-sectional dependence and three estimator robustness checks (PMG-ARDL, DOLS, FMOLS), the study results in several important findings.

Firstly, GG and GTI contribute effectively to mitigating CO_2 emissions in the long term, proving the research hypotheses based on the theory of sustainable development, the Porter Hypothesis, and natural capital theory. The abatement effect of GTI (0.65%) is more significant than that of GG (0.38%), which implies that the innovative efficiency effect is especially powerful in terms of CO_2 emissions reduction. Secondly, the EKC hypothesis is verified for BRICS, where CO_2 emissions increase with GDP growth, while the negative GDP squared effect demonstrates that, beyond a certain level of GDP growth, the further maturity of an economy is related to environmental improvement. Thirdly, FDI contributes to verifying the Pollution Halo Hypothesis by spreading cleaner technologies in BRICS host economies. Fourthly, fossil fuel use and population growth positively affect CO_2 emissions. Fifth, through Granger Causality tests, it is shown that GG and GTI unilaterally cause changes in LED, proving that green investment is indeed an effective tool without any negative feedbacks on emissions. Sixth, the diagnostics and stability tests confirm the validity of the results obtained from our model.

6.2 Policy Implications

These results hold practical implications for BRICS decision-makers. First, considering that GTI lowers emissions by about 0.65%, governments need to focus on developing innovation incentive mechanisms: green patent boxes and R&D tax credits, renewable energy subsidy programmes, and green innovation contests. Establishment of a joint BRICS green technology fund akin to the Green Climate Fund would help to capitalize on international knowledge spillovers. Second, considering the GG effect (-0.38% per unit), it would be sensible to invest in energy-efficient infrastructure such as green smart electricity networks, low-carbon urban transportation systems, and green industrial zones. Third, FDI effects support designing frameworks whereby foreign investors would have to adopt environmentally-friendly production techniques. Fourth, considering that the use of fossil fuels still increases emissions, there is an urgent need to introduce some kind of carbon pricing mechanism, either carbon taxation or emissions trading system, which would address the current market failure. Fifth, given that the growth of population leads to more CO2 emissions, it would be reasonable to allocate some funds to promote environmentally-friendly urban mobility, energy-efficient housing, and sustainable agricultural practices, especially in the countries with high rates of population growth like India and South Africa.

6.3 Limitations and Future Directions

There are several areas of future research that warrant consideration. The first area concerns the estimation of GG through environmentally adjusted multifactor productivity, which can measure the aggregate level of efficiency without taking into account the effects in individual sectors; future research should incorporate the analysis using GTI and GG at the sectoral level. Another area that should be considered is that of institutional governance effectiveness, rule of law, and strict regulation. Third, the adoption and diffusion of specific green technologies (e.g., solar capacity installed, electric vehicle penetration) could be substituted for patent-count-based GTI to better capture deployment rather than innovation output alone. Fourth, sub-national and regional analyses within BRICS countries could illuminate within-country heterogeneity in emissions trajectories and green transition progress. Fifth, the application of nonlinear or threshold-regression models could test whether the EKC and GTI-emissions relationships are regime-dependent across income or institutional quality thresholds.

Declarations

Author Contributions

Rana Zain ul Abidin and Rabia Qammar: Conceptualization, Methodology, Formal Analysis, Writing Original Draft. Muhammad Abdullah khan and Omar Abd-Aljaber Data Curation, Validation, Writing Review and Editing.

Data Availability Statement

The data used in this study are publicly available from the World Development Indicators (https://data.worldbank.org), the OECD Statistics database (https://stats.oecd.org), and the WIPO IP Statistics Data Centre (https://www.wipo.int/ipstats). The dataset compiled for this analysis is available from the corresponding author upon reasonable request.

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