

CLEAN ENERGY TRANSITION AND TECHNOLOGICAL INNOVATION FOR ENVIRONMENTAL SUSTAINABILITY: NEW EVIDENCE FROM LOAD CAPACITY FACTOR AND QUANTILE DYNAMICS IN BRICS ECONOMIES

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Abstract

Environmental sustainability is a critical challenge for developing economies, particularly the BRICS nations, given their significant contributions to global economic activity and the environmental pressures they face. This study investigates the effects of technological innovation ($\ln TI$), renewable energy consumption ($\ln REC$), natural resource rents ($\ln NRR$), economic growth ($\ln GDP$), and trade openness ($\ln TO$) on environmental sustainability in BRICS economies from 2000 to 2024. The study employs an integrated econometric framework incorporating slope heterogeneity, CSD, second-generation unit root, and Westerlund cointegration tests, followed by the Method of Moments Quantile Regression (MMQR) to capture heterogeneous effects across the conditional distribution of Load Capacity Factor (LCF). The findings reveal that technological innovation significantly reduces LCF at lower and middle quantiles but is not significant at higher quantiles, signifying that technological progress does not uniformly increase environmental sustainability. In contrast, $\ln REC$, $\ln NRR$, and $\ln GDP$ positively and significantly enhance LCF across all quantiles. $\ln TO$ consistently hurts LCF, supporting the pollution haven hypothesis. The results remain robust when estimated using FGLS. These findings underscore the importance of accelerating the adoption of renewable energy, leading technological innovation toward environmentally efficient applications, enhancing the management of natural resource revenues, and encouraging environmentally reliable trade policies. Overall, the study highlights the need for differentiated policy strategies that reflect the heterogeneous environmental conditions of BRICS economies.

1. Introduction

Environmental sustainability is one of the greatest challenges of the twenty-first century, and climate change, ecosystem degradation, biodiversity loss, and resource depletion are now undermining sustainable development (Pörtner et al., 2022). Continued reliance on traditional energy, rapid industrialization, and economic development have placed a greater burden on natural ecosystems through increased energy use, resource depletion, and GHG emissions (Apergis et al., 2023; Khalid et al., 2026). This challenge has shifted the focus away from emissions reduction and from the question of whether it is possible to have an economy that operates within nature's regenerative limits. Traditional indicators such as carbon emissions and ecological footprint provide only a partial picture of environmental pressures and have limited information on ecological capacity. The LCF overcomes this by taking an ecological footprint and biocapacity approach, which corresponds to the relationship between ecological demand and nature's capacity to supply. An ecological LCF >1 indicates an ecological surplus; and an ecological LCF <1 indicates an ecological deficit. Thus, LCF is a more holistic measure of environmental sustainability that links human ecological requirements to the capacity of natural systems to meet those requirements.

The environmental impacts of economic development are increasingly dependent on how economies transform energy, technology, natural resources, and international trade. Technological innovation (TI) can increase the efficiency of energy use, lower the resource intensity (Zafar et al., 2025) and facilitate cleaner production processes, but it can also boost production, consumption, and energy demand, which can lead to rebound effects that mitigate the ecological impacts (Khalid et al., 2026; Almulhim et al., 2025; Muhammad et al., 2025). Renewable energy consumption (REC) plays an essential role in the clean energy transition, as the fossil fuel phase-out can reduce the ecological burden and enhance environmental sustainability (Samour et al., 2024; Georgescu & Kinnunen, 2026; Ullah

et al., 2023). Likewise, the environmental contribution of natural resource rents (NRR) is also not clearly defined, as the revenues generated from natural resources may be used for technological upgrading and environmental investments (Hammami et al., 2025; Liang & George, 2026; Zafar et al., 2026). In contrast, rising lnGDP can increase ecological pressures through production and resource consumption, whereas higher income can enable cleaner technologies and environmental protection, as suggested by the EKC and LCC strands (Siche et al., 2010; (Grossman & Krueger, 1995). The environmental impacts of trade openness (TO) can also act in opposite directions with respect to scale, composition, and technology. The competing mechanisms suggest that the environmental impact of these determinants is unlikely to remain constant across all levels of ecological sustainability.

The BRICS economies¹ offer a particularly relevant context for considering these relationships. They are major emerging economies, categorized by high growth and energy consumption rate, high natural resource utilization and high environmental pressures (World Bank, 2024; Energy Institute, 2024). However, there are significant differences in their environmental structures. Brazil is endowed with vast natural-resource and renewable-energy potential; Russia is extremely resource-dependent; China and India have seen rapid industrial and technological growth; and South Africa remains highly dependent on fossil fuels. These disparities reduce the likelihood of similar environmental impacts from technological innovations, clean energy, resource rents, economic growth, and trade openness across the BRICS. So, asking whether or not these factors matter for environmental sustainability is not enough; the question is whether their impact differs across ecological performance levels. While research on environmental sustainability in BRICS is increasingly abundant, three significant gaps remain. First, much of the

¹ Brazil, Russia, India, China, and South Africa

literature uses CO₂ emissions or ecological footprints, which are not ideal measures of the relationship between ecological demand and biocapacity.

While recent studies have increasingly used the LCF, evidence for BRICS remains relatively scattered. Second, many previous studies attention on average effects and may overlook significant differences through economies with low and high levels of environmental sustainability. Third, although there has been recent work on technological innovation, renewable energy, natural resources, and LCF in BRICS, the distributional relationship between technological innovation and the clean energy transition remains under-researched. This is important because technological innovation could increase ecological stress in the short term by, for example, increasing production and energy use, and also bring environmental benefits; the impact of renewable energy could be dependent on the specific ecological setting of the economy. For instance, the latest BRICS evidence reveals that green innovation and green transitions can have various impacts on the LCF distribution (Uche et al., 2024), and different studies have reported conflicting results on the effect of technological innovation, renewable energy, and natural resources on LCF (Zhao et al., 2023; Voumik et al., 2024; Sun & Qamruzzaman, 2025). Such mixed results point to the need for a distribution-sensitive analysis.

Given this backdrop, this study examines the mixed impact of lnTI, lnREC, lnNRR, lnGDP, and lnTO on LCF in the BRICS economies from 2000 to 2024. The study employs the MMQR proposed by Machado and Santos Silva (2019), which allows the impact of the independent variables to vary rather than taking a single average impact. It is a suitable framework for BRICS, as each country may respond differently to technological change, resource dependence, GDP growth, and trade integration. CSD, slope heterogeneity, 2nd-generation unit-root, and Westerlund cointegration tests are used to sustain the analysis, and FGLS estimates are used to assess the robustness of the findings. This study

adds to the literature in three ways. First, it relies on the LCF as a fundamental indicator of environmental sustainability, which accounts for both ecological demand and bio-capacity and not only for emissions and ecological pressure. Second, it uses the MMQR to reveal variation in the environmental impact of lnTI, lnREC, lnNRR, lnGDP, and lnTO across the LCF distribution, which conventional mean-based estimates may obscure. Thirdly, the study offers fresh evidence on the association between technological innovation and the clean energy transition in an economy with different energy mixes, resource availabilities, and environmental conditions by examining the BRICS economies between 2000 and 2024. The results thus provide a foundation for more targeted policies to harmonies technological progress, the increase in renewable energy, and the handling of resources and trade with ecological capacities.

The rest of the study is structured as follows. The hypotheses are developed, and the related theoretical and empirical literature is reviewed in Section 2. The data, variables, model specification and econometric methodology are presented in Section 3. The results of the empirical analysis and robustness test are reported and discussed in Section 4. Conclusions and policy implications are provided in Section 5.

2. Literature Review

Environmental sustainability research has increasingly moved away from traditional indicators such as CO₂ emissions and ecological footprint towards indicators that provide a more comprehensive picture of ecological balance. The LCF has been developed to combine ecological footprint and biocapacity, indicating ecological demand and nature's ability to regenerate. A value of LCF > 1 suggests an ecological surplus, while LCF < 1 suggests an ecological deficit. Recent research indicates that renewables, technology, natural resources, and economic activity have significant impacts on LCF, which vary by country and empirical context (Mehmood et al., 2023; Adebayo & Samour, 2024). Such conflicting results have raised questions about

whether the environmental impacts of these determinants vary with the environment's performance.

2.1. Technological Innovation and Load Capacity Factor

Technological Innovation (InTI) has long been acknowledged as a key enabler of environmental sustainability, as it can lead to energy efficiency, lower resource intensity, cleaner production, and faster uptake of green technologies. But technological advances have not always led to improvements in the environment. Another rebound effect may be an increase in production and consumption, and consequently in the energy demand. Its net environmental impact has thus been determined by whether technological expansion has been accompanied by increased resource utilization.

The empirical data have been inconsistent. Mehmood et al. (2023) revealed that technological development has improved LCF in G8 economies, and Anas et al. (2024) demonstrated that green technological innovation has improved environmental sustainability in emerging economies. But the evidence has been less conclusive from BRICS economies. Zhao et al. (2023) reported conflicting environmental impacts of technological innovation, while Uche et al. (2024) found that green technologies have had a smaller impact on LCF than the green transition as a whole. Hammami et al. (2025) also showed that the impacts of technological innovation varied across LCF quantiles, with distinct positive environmental outcomes at certain points along the distribution. The overall results indicate that the environmental impact of innovation has been inconsistent and may be contingent on the quality of ecological performance.

H1: Technological innovation (InTI) has a heterogeneous effect on the LCF across its conditional distribution in BRICS economies.

2.2. Renewable Energy Consumption and Load Capacity Factor

Renewable energy consumption (REC) has been considered a central pillar of the clean energy transition. Switching from fossil fuels to renewable energy sources can help to decrease energy intensity, minimize environmental impact, and increase ecological sustainability. Overall, the literature provides more evidence of a positive impact of REC on LCF than of technological innovation on LCF. Ojekemi, et al. (2023) found evidence of how REC had improved LCF in G8 economies, and Zhao et al. (2023) reported evidence for BRICS-T economies. Evidence from BRICS has further supported this relationship. Adebayo and Samour (2024) demonstrated how REC increased environmental sustainability, and Li et al. (2024) revealed a positive relationship between renewable energy and LCF. Uche et al. (2024) also showed that ecological load capacity has been improved across the distribution with the help of the green transition. Hammami et al. (2025) also found that clean energy had strengthened LCF, particularly at lower and middle quantiles. However, the magnitude of these increases has varied across energy systems, renewable energy infrastructure, technological capabilities, and the extent of fossil-fuel substitution by renewables. This evidence provides a solid foundation for expecting a positive relationship between REC and LCF.

H2: Renewable energy consumption (InREC) has a positive effect on the LCF across the conditional distribution in BRICS economies.

2.3. Natural Resource Rents and Load Capacity Factor

Natural resource rents (NRR) both provide economic opportunities and create environmental pressures. The resource curse argument suggests that reliance on resource extraction may contribute to faster ecological deterioration through resource-intensive production, overexploitation, pollution, and inadequate diversification of the economy. But under good management, resource revenues can also sponsor investments in renewable energy,

technological improvements, and environmental protection.

The existing LCF literature has predominantly supported the adverse environmental consequences of resource dependence. Zhao et al. (2023) reported that natural resources had reduced LCF in BRICS-T economies, while Li et al. (2024) found that natural-resource dependence had deteriorated ecological quality in BRICS. Yang et al. (2024) similarly identified negative effects of natural resources across the LCF distribution. Sun and Qamruzzaman (2025) further showed that natural resources had remained an important determinant of environmental sustainability in BRICS+T economies. However, differences in resource dependence, institutional quality, resource management practices, and environmental conditions suggest that the magnitude of this relationship may not have remained constant across the LCF distribution. Accordingly, the environmental consequences of natural resource rents warrant examination beyond their average effect.

H3: Natural resource rents (lnNRR) have a heterogeneous effect on the LCF across its conditional distribution in BRICS economies.

2.4. Economic Growth and Load Capacity Factor

The relationship between economic growth and environmental sustainability has remained theoretically ambiguous. The Environmental Kuznets Curve (EKC) hypothesis posits that environmental degradation may increase with economic development and then begin to reverse once economic growth reaches higher levels, as countries switch to less resource-intensive production processes, improve environmental regulation, or develop cleaner technologies (Grossman & Krueger, 1995). The Load Capacity Curve (LCC) approach has taken this debate further by linking economic growth to ecological demands and biocapacity. Growth can strain ecological capacity, as production, energy use, resource extraction, and transportation grow. This concern has been corroborated by several

studies in BRICS economies. Economic growth was associated with environmental degradation, as reported by Adebayo and Samour (2024), Li et al. (2024), and Qin et al. (2025), which reported a negative effect of economic growth on all LCF quantiles. In contrast, Voumik et al. (2024) found a positive association between economic growth and LCF in BRICS, implying that economic growth could be conducive to environmental improvement under specific economic and institutional settings. The mixed findings have thus pointed to the possibility of a differential growth–environment relationship.

H4: Economic growth (lnGDP) has a heterogeneous effect on the LCF across its conditional distribution in BRICS economies.

2.5. Trade Openness and Load Capacity Factor

Trade openness (lnTO) can influence environmental sustainability through scale, composition, and technique effects. The increased integration of trade may expand production activities, resource extraction, transportation, and energy utilization, which may put greater pressure on the environment. The Pollution Haven Hypothesis has also postulated that pollution-intensive activities relocate to countries with relatively less stringent environmental laws (Copeland & Taylor, 2004). Meanwhile, international trade can facilitate technology transfer and provide access to cleaner capital goods and more efficient production processes.

There is no conclusive empirical evidence regarding the relationship between trade and LCF. Sun and Qamruzzaman (2025) demonstrated varying environmental impacts in BRICS+T economies with respect to different environmental indicators in the context of trade openness, technological innovation, and natural resources and clean energy. These distinctions have highlighted the need for LCF as an ecological capacity indicator and have cast doubt on the transferability of concepts developed based on emissions or ecological footprints to environmental sustainability more broadly. Furthermore, the diverse nature of export

baskets, the resource intensities of the BRICS economies, and their technological levels suggest that the impacts of trade may vary across environmental performance levels.

H5: Trade openness ($\ln TO$) has a heterogeneous effect on the LCF across its conditional distribution in BRICS economies.

Overall, the literature has suggested that the environmental effects of technological innovation, renewable energy consumption, natural resource rents, economic growth, and trade openness have not been uniform across economies or levels of ecological performance. This evidence has provided a rationale for moving beyond average-effect estimators and examining the conditional distribution of LCF. Accordingly, this study has employed MMQR to

assess whether the effects of these five determinants have varied across different levels of environmental sustainability in BRICS economies, with particular attention to the contrasting roles of technological innovation and renewable energy in the clean energy transition.

3. Methodology

This study uses an annual balanced panel dataset for the BRICS economies, including Brazil, Russia, India, China, and South Africa, over the period 2000 to 2024 ($N = 5$, $T = 25$, $N \times T = 125$). The purpose of the study is to examine the impact of $\ln TI$, $\ln REC$, $\ln NRR$, $\ln GDP$, and $\ln TO$ on the Load Capacity Factor (LCF). The variable descriptions, data sources, and their measurements are displayed in Table 1.

Table 1: Variable Description

Variable	Symbol	Measurement Unit	Data Source
Load Capacity Factor	$\ln LCF$	Biocapacity / Ecological Footprint ratio	GFN
Technological Innovation	$\ln TI$	R&D expenditures (% of GDP)	WDI
Renewable Energy	$\ln REC$	Renewable energy consumption (% of total energy)	WDI
Natural Resource Rents	$\ln NRR$	Total natural resource rents (% of GDP)	WDI
Economic Growth	$\ln GDP$	GDP per capita (constant 2015 US\$)	WDI
Trade Openness	$\ln TO$	Sum of exports and imports (% of GDP)	WDI

3.1 Model Specification

The Baseline Model

The empirical model is specified within a panel-data framework to examine the determinants of environmental sustainability, measured by the LCF, across the BRICS economies.

The log-linear econometric model is specified as:

$$\ln LCF_{it} = \alpha_0 + \beta_1 \ln TI_{it} + \beta_2 \ln REC_{it} + \beta_3 \ln NRR_{it} + \beta_4 \ln GDP_{it} + \beta_5 \ln TO_{it} + \mu_i + \varepsilon_{it}$$

where i indicates the country and t denotes the time period. ($\ln TI$), ($\ln REC$), ($\ln NRR$), ($\ln GDP$), and ($\ln TO$) denote technological innovation, renewable energy consumption, natural resource rents, economic growth, and trade openness, respectively. The parameter α represents the constant term, whereas β_1 to β_5 capture the marginal effects of the explanatory variables on environmental sustainability. The term μ captures unobserved country-specific fixed effects that remain constant over time, while ε_{it} signifies the idiosyncratic error term that

accounts for unobserved factors varying across countries and over time.

3.2. Empirical Strategy

The current study adopts a step-by-step econometric strategy to address key panel-data challenges and account for the distinct factors affecting environmental sustainability across the BRICS countries. The CSD test and the slope heterogeneity test proposed by Pesaran and Yamagata (2008) are first applied to examine cross-sectional interdependence and parameter variation across countries. Second, since there is cross-sectional dependence, stationarity is tested using the second-generation CIPS Panel Unit Root test. After this, the Westerlund (2007) bootstrap cointegration test is used to assess the presence of a long-term equilibrium relationship between the variables while controlling for cross-

sectional dependence. Given these diagnostic findings and the identified cross-sectional dependence, slope heteroscedasticity, serial correlation, and group wise heteroscedasticity, the primary analysis employs the Method of Moments Quantile Regression (MMQR) with fixed effects introduced by Machado and Santos Silva (2019). The MMQR framework is estimated at quantiles from the 10th to the 90th, enabling the study to identify potential differential and distribution-specific effects across different levels of environmental quality. Finally, as an additional test of the stability and reliability of the MMQR results, the FGLS estimator is used as a robustness check to account for complicated error structures, including heteroscedasticity and serial correlation. Note figure 1 display Step-by-step empirical strategy of the study.

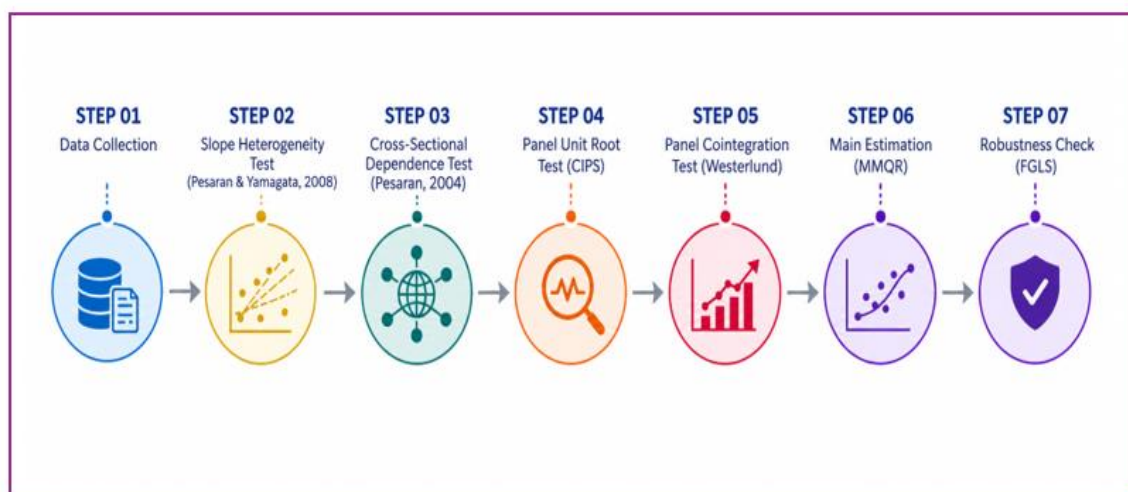


Figure 1. Step-by-step empirical strategy of the study

4. Results and Interpretation

Descriptive statistics includes providing basic information about the data by summarizing and describing the data's main features (Gul et al., 2023). In Table 2 reports the descriptive statistics results which indicating considerable variation in environmental sustainability across the BRICS nations. The mean values of $\ln TI$, $\ln REC$, $\ln NRR$, $\ln GDP$, and $\ln TO$ are 0.012, 2.741, 1.575, 8.526, and 3.752, respectively. The standard deviations also show substantial

variation across countries and over time, supporting the use of panel-data methods. Correlation matrix results reports in Table 3 indicate that $\ln TI$ and $\ln REC$ have weak positive correlations with $\ln LCF$, while $\ln NRR$ and $\ln GDP$ are more strongly and positively correlated with $\ln LCF$. In contrast, $\ln TO$ is negatively correlated with $\ln LCF$. Figure 2 display the correlation Heatmap and presents a visual summary of these relationships. Among the explanatory variables, the strongest correlations

are between $\ln\text{REC}$ and $\ln\text{NRR}$ and between $\ln\text{REC}$ and $\ln\text{TO}$. However, the VIF results in Table 3A show no serious multicollinearity. The maximum VIF is 3.63 and the mean VIF is 2.46,

both below conventional thresholds. Therefore, multicollinearity is unlikely to bias the regression coefficients.

Table 2. Descriptive Statistics Results

Variable	Obs.	Mean	Std. Dev.	Min	Max
$\ln\text{LCF}$	125	-0.317	0.977	-1.554	1.409
$\ln\text{TI}$	125	0.012	0.379	-0.505	1.021
$\ln\text{REC}$	125	2.741	0.956	1.163	3.912
$\ln\text{NRR}$	125	1.575	0.776	-0.146	3.233
$\ln\text{GDP}$	125	8.526	0.754	6.629	9.481
$\ln\text{TO}$	125	3.752	0.278	3.095	4.220

Table 3. Correlation Matrix Results

	$\ln\text{LCF}$	$\ln\text{TI}$	$\ln\text{REC}$	$\ln\text{NRR}$	$\ln\text{GDP}$	$\ln\text{URB}$
$\ln\text{LCF}$	1.0000					
$\ln\text{TI}$	0.0278	1.0000				
$\ln\text{REC}$	0.1042	-0.0867	1.0000			
$\ln\text{NRR}$	0.3156	-0.1839	-0.6420	1.0000		
$\ln\text{GDP}$	0.4298	0.5143	-0.4578	0.2695	1.0000	
$\ln\text{TO}$	-0.5353	-0.2391	-0.6373	0.5020	-0.1108	1.0000

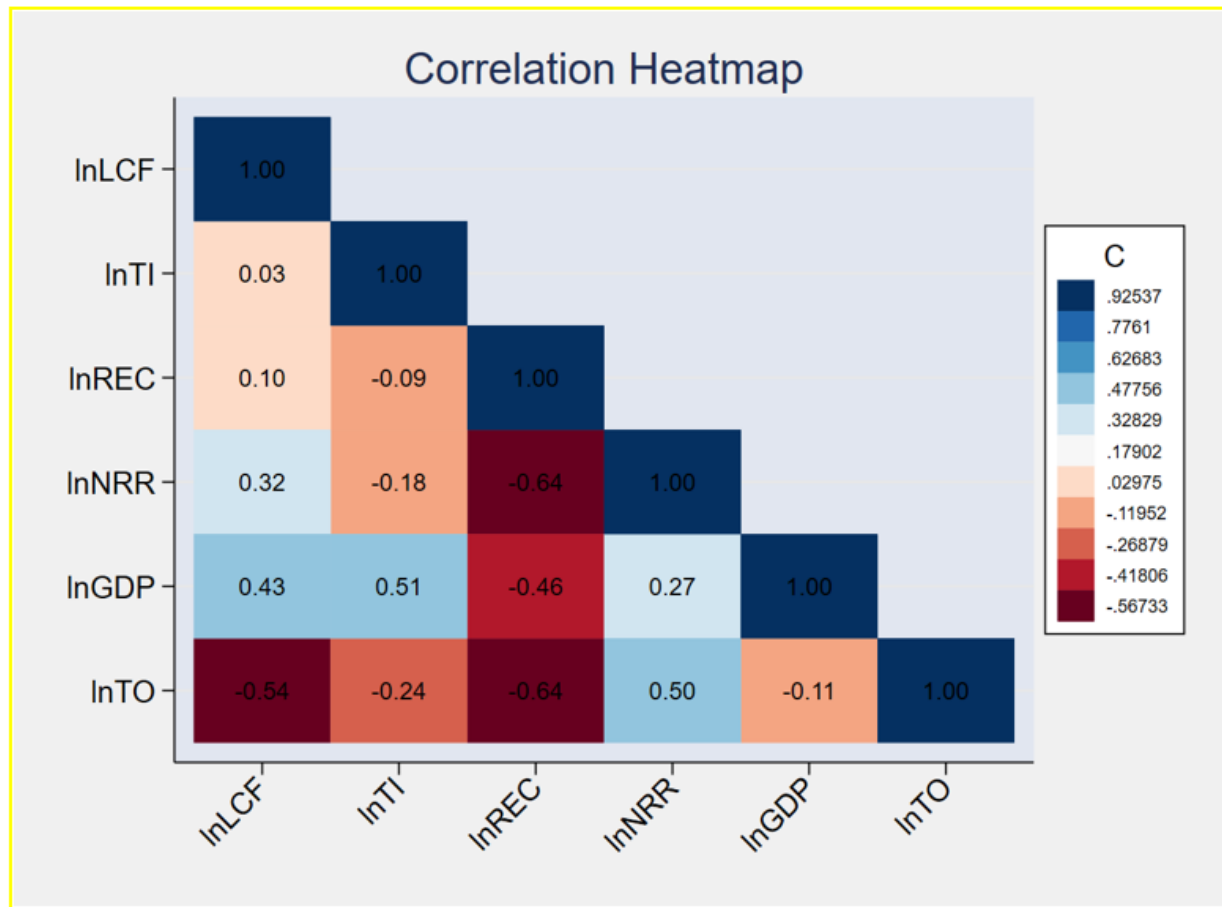


Figure 2: Correlation Heatmap

Table 3A. Variance Inflation Factor (VIF) Results

Variable	VIF	1/VIF
lnREC	3.63	0.2754
lnTO	2.65	0.3770
lnGDP	2.45	0.4087
lnNRR	1.98	0.5051
lnTI	1.61	0.6201
Mean VIF	2.46	—

Table 4 presents the findings of the slope heterogeneity tests developed by Pesaran and Yamagata (2008). The null hypothesis of homogeneous slopes is rejected by both the Delta statistic and the adjusted Delta statistic. The effects of the explanatory variables are not the same across all BRICS countries. Figure 3 gives a visual assessment of the slope heterogeneity results. This can help to support the use of an

estimator that allows the relationships to vary across countries and across the distribution of environmental sustainability. Moreover, Table 5 reports CSD results indicating that the null hypothesis of cross-sectional independence is rejected for lnLCF and most explanatory variables. In contrast, trade does not show notable CSD. The presence of CSD implies that shocks may be transmitted among BRICS

economies through trade, investment, and other economic linkages. Consequently, these interdependencies need to be accounted for in the estimation approach.

Given the existence of CSD, the stationarity properties of the variables are evaluated using the Pesaran (2007) CIPS test, with the results presented in Table 6. The results show that $\ln TI$ is stationary at level under the constant

specification, with a test statistic of -2.613 ($p < 0.05$). In contrast, $\ln LCF$, $\ln REC$, $\ln NRR$, $\ln GDP$, and $\ln TO$ are non-stationary at levels but are stationary after first differencing. Consequently, the variables are integrated up to first order, but not beyond. The results of the Westerlund (2007) cointegration tests are presented in Table 7, which confirm long-run equilibrium among the study variables.

Table 4. Slope Heterogeneity Test Results

Test statistic	Value	p-value	Decision
Δ	4.905	0.000	Reject H_0
$Adj - \Delta$	5.781	0.000	Reject H_0

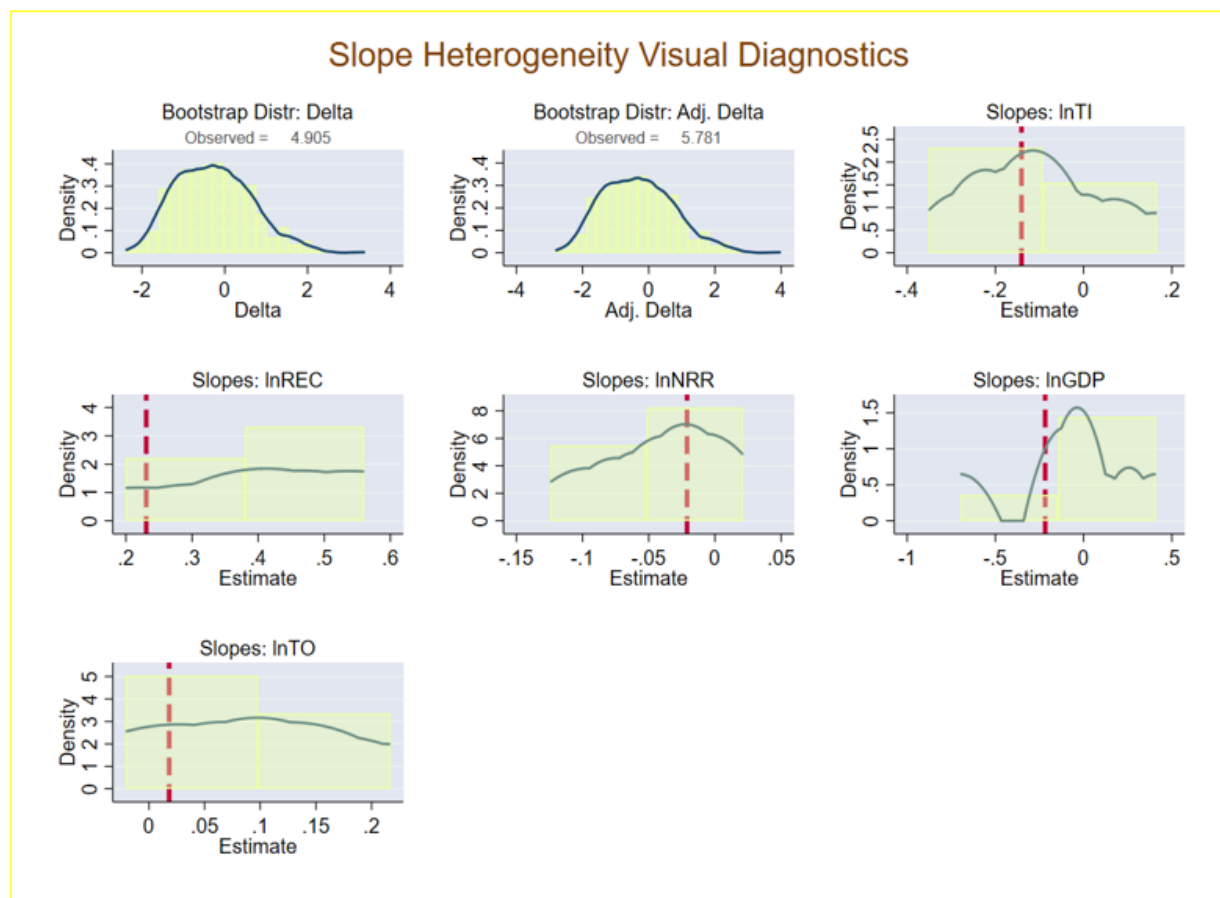


Figure 3: Visual Diagnostic of the Slope heterogeneity.

Table 5. Pesaran Cross-Sectional Dependence Test

Variable	Pesaran CD	p-value	CSD at 5%
$\ln LCF$	4.820	0.000	Yes
$\ln TI$	-2.290	0.022	Yes

lnREC	4.146	0.000	Yes
lnNRR	9.316	0.000	Yes
lnGDP	13.777	0.000	Yes
lnTO	-1.039	0.299	No

Table 6. Pesaran CIPS Panel Unit Root Test

Variable	Level	First Difference	Order
lnLCF	-2.115	-4.235***	I(1)
lnTI	-2.613**	-5.158***	I(0)
lnREC	-1.203	-3.419***	I(1)
lnNRR	-1.681	-5.371***	I(1)
lnGDP	-1.888	-2.853***	I(1)
lnTO	-1.339	-3.822***	I(1)

*** $p < .01$, ** $p < .05$, * $p < .1$

Table 7. Westerlund (2007) Cointegration Test

Statistic	Value	p-value	Decision
Gt	-1.753	0.007***	Reject H_0
Ga	-5.317	0.996	Do not reject H_0
Pt	-3.911	0.018**	Reject H_0
Pa	-5.398	0.866	Do not reject H_0

*** $p < .01$, ** $p < .05$, * $p < .1$

Table 8 shows the diagnostic results for serial correlation, heteroscedasticity, and individual effects. The Wooldridge test results in the rejection of the null hypothesis of no first-order autocorrelation, indicating the presence of serial correlation. Similarly, the null hypothesis of homoscedasticity is rejected by the Modified Wald test, pointing to GroupWise heteroscedasticity. In addition, the individual-

effects test is statistically significant, confirming the presence of country-specific effects. Overall, the diagnostic tests detect CSD, slope heterogeneity, serial correlation, heteroscedasticity, and country-specific effects. These properties suggest an estimation strategy that can allow for heterogeneous effects across the environmental sustainability distribution.

Table 8. Panel Diagnostic Tests

Diagnostic test	Statistic	p-value	Decision	Implication
Wooldridge test for serial correlation	$F(1,4) = 12.049$	0.0256	Reject H_0	First-order autocorrelation
Modified Wald test for GroupWise heteroscedasticity	$\chi^2(5) = 163.31$	0.0000	Reject H_0	GroupWise heteroscedasticity
Fixed-effects test: all unit effects = 0	$F(4,120) = 2015.36$	0.0000	Reject H_0	Unit effects are significant

Given the diagnostic evidence for CSD, SH, non-stationarity, and cointegration, the MMQR is employed to capture how explanatory variables influence the conditional distribution of the logistics carbon footprint rather than relying on a single average effect, an approach well suited to BRICS economies where environmental determinants vary across countries. The results for MMQR are reported in Table 9: technological innovation (lnTI) is found to be negatively and significantly related to logistics carbon footprint at the lower and middle quantiles (q10–q70), but the impact becomes less pronounced at the top quantiles, and is insignificant at q90, suggesting that technological progress could even worsen environmental pressure when environmental performance is poor, and that environmental positive impact becomes less significant as environmental performance improves, consistent with Khalid et al. (2026) and Li et al. (2023). lnREC is positively and significantly associated with lnLCF at all quantiles, consistent with the findings of Alnuhaim et al. (2025) and Khalid et al. (2026), indicating that higher renewable energy consumption is associated with better environmental outcomes, such as decreasing dependence on fossil fuels and improving energy quality. There is also a positive and significant relationship at all quantiles for natural resource rents (lnNRR), with the coefficients increasing with quantiles, implying that under some conditions, natural resource revenues could contribute to environmental investment, consistent with Liang and George (2026) showing that a 1% increase in natural resource rents leads to an approximately 0.21% rise in CO₂ emissions in the BRICS economies. Similarly, lnGDP also shows a positive and significant correlation with lnLCF for all quantiles, with the coefficients increasing from 0.474 at q10 to 0.442 at q90, indicating that economic development is related to environmental sustainability throughout the

distribution. Still, the correlation decreases in the upper quantiles, which may be due to the impact of economic growth on infrastructure, environmental investment, technological capacity (Khan et al., 2023; Khan et al., 2023), and resource efficiency, consistent with the Environmental Kuznets Curve phenomenon in which environmental pressure first increases with income and then decreases after a threshold level. Trade shows a significant and strong negative connection across all the quantiles, which is the strongest negative link among all the explanatory variables, meaning that higher levels of trade openness can increase environmental pressures, as it is associated with more resource-intensive production, energy consumption, and export-oriented activities, consistent with Georgescu and Kinnunen (2026). Figure 4 and 4A reports the MMQR estimates on the 10th–90th quantiles of lnLCF and a significantly heterogeneous effect of the explanatory variables across the conditional distribution of environmental sustainability is found, with the coefficient for lnTI decreasing monotonically over the quantiles, reflecting the fact that the negative effect of technological innovation on the environment is greater at lower quantiles; the coefficient for lnREC is slightly increasing because the contribution of renewable energy to environmental sustainability seems to be higher at higher quantiles; the coefficient for lnNRR is significantly increasing, and the coefficient for lnGDP is slightly decreasing, suggesting that the impact of GDP on environmental sustainability is lower at higher quantiles; and the coefficient for lnTO is significantly decreasing, indicating that the impact of trade is more negative at higher quantiles, all of which highlight the need for quantile-based analysis to capture the heterogeneous effect of the explanatory variables at different levels of environmental sustainability.

Table 9: MMQR Test Results

Variable	q10	q20	q30	q40	q50	q60	q70	q80	q90
lnTI	-	-	-	-	-	-	-0.364**	-0.299*	-0.229

	0.728** * (0.185)	0.654** * (0.163)	0.585** * (0.148)	0.521** * (0.139)	0.472** * (0.136)	0.409** * (0.138)	(0.144)	(0.157)	(0.178)
lnREC	0.222* (0.120)	0.224** (0.105)	0.227** (0.095)	0.229** (0.089)	0.231** * (0.087)	0.233** * (0.089)	0.235** (0.093)	0.237** (0.102)	0.239** (0.115)
lnNRR	0.733** * (0.104)	0.780** * (0.092)	0.823** * (0.083)	0.863** * (0.078)	0.894** * (0.076)	0.933** * (0.077)	0.962** * (0.081)	1.003** * (0.088)	1.047** * (0.100)
lnGDP	0.474** * (0.104)	0.469** * (0.091)	0.465** * (0.082)	0.460** * (0.077)	0.457** * (0.076)	0.453** * (0.077)	0.451** * (0.081)	0.446** * (0.088)	0.442** * (0.099)
lnTO	2.460** * (0.307)	2.489** * (0.270)	2.515** * (0.243)	2.539** * (0.228)	2.558** * (0.224)	2.581** * (0.229)	2.599** * (0.238)	2.623** * (0.261)	2.650** * (0.294)
_cons	2.564 (1.987)	2.791 (1.747)	3.003* (1.576)	3.198** (1.478)	3.350** (1.451)	3.541** (1.480)	3.680** (1.545)	3.881** (1.692)	4.094** (1.904)

*** $p < .01$, ** $p < .05$, * $p < .1$

Finally, to confirm the MMQR results, we applied FGLS as a robustness check, as reported in Table 10. The findings are quite strong: trade openness remains negatively and significantly related to lnLCF, and all other study variables are positive and significant, maintaining the strong negative association with lnTO. Stability is

ensured because all coefficients have the same sign as the MMQR estimates. However, MMQR remains the main estimator because it captures varying magnitudes of association across the environmental sustainability distribution, whereas the FGLS provides a conditional mean.

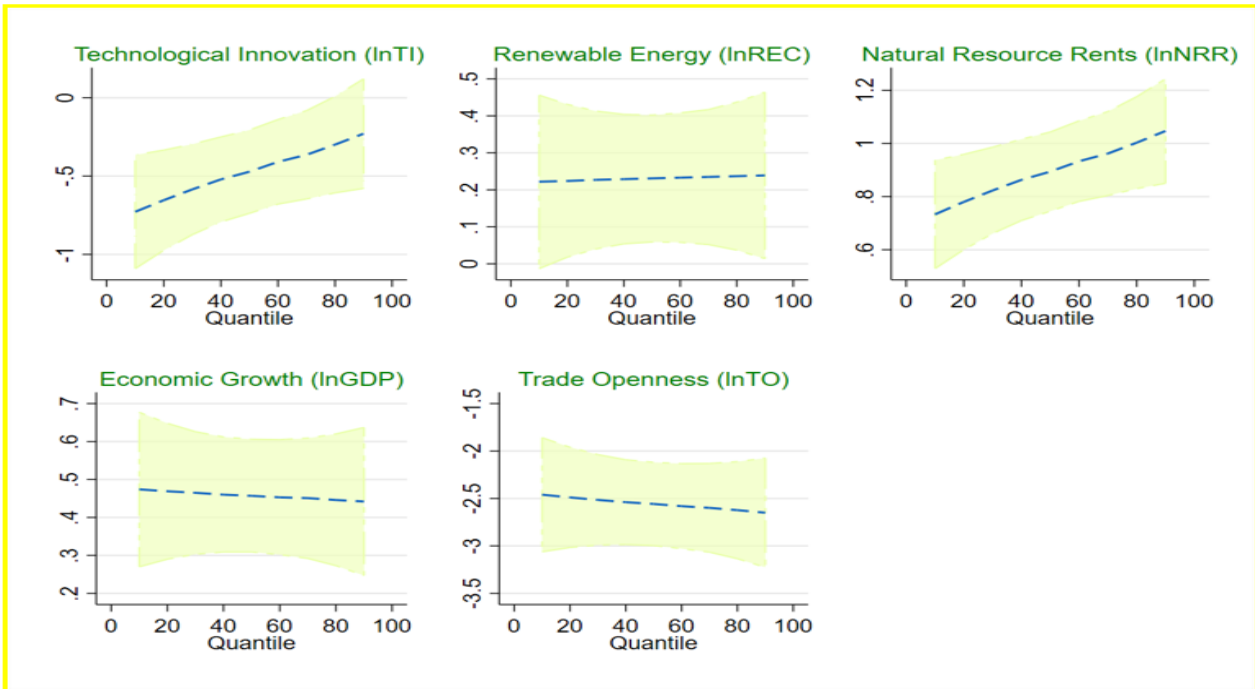


Figure 4: MMQR Coefficient Plots Across Quantiles

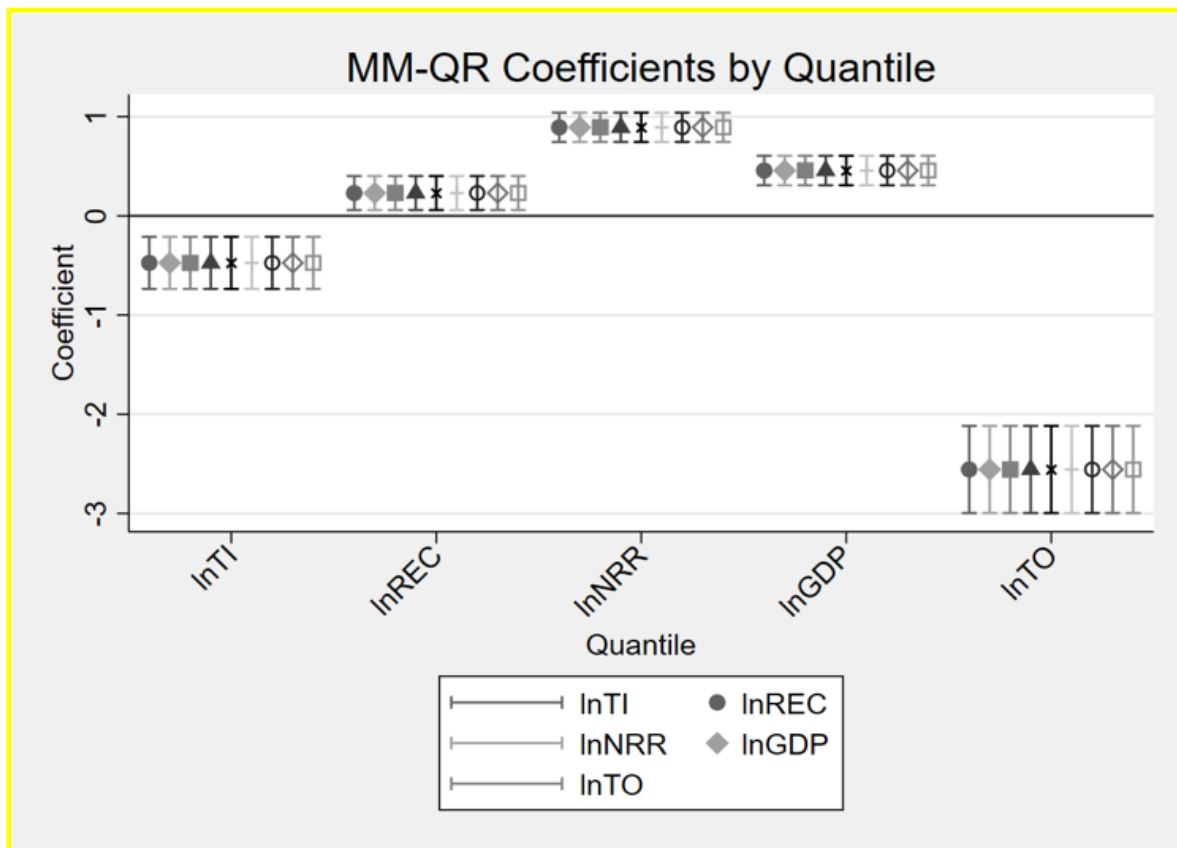


Figure 4A: Quantile-Varying Coefficients of Determinants of Environmental Sustainability.

Table 10: FGLS Robustness Test Results

Variable	Coef (SE)	p-value	Sig
lnTI	-0.399(0.122)	0.001	***
lnREC	0.272(0.079)	0.001	***
lnNRR	0.859(0.071)	0.000	***
lnGDP	0.471(0.073)	0.000	***
lnTO	-2.477(0.214)	0.000	***
_cons	2.834(1.379)	0.04	**

*** $p < .01$, ** $p < .05$, * $p < .1$

5. Conclusion and Policy Recommendations

This study investigated the heterogeneous effects of technological innovation along with macroeconomic, environmental and sustainable variables in BRICS economies from 2000 to 2024. Using the MMQR validated by FGLS, the findings show that technological innovation negatively affects LCF at lower and middle quantiles but turns insignificant at higher quantiles; renewable energy consumption consistently enhances LCF across all quantiles; natural resource rents exhibit a positive association, suggesting that resource revenues can support environmental investment when managed effectively; economic growth positively impacts LCF through improved infrastructure and technological capacity, though the effect diminishes at higher quantiles; and trade openness exerts the strongest negative impact on LCF, supporting the pollution haven hypothesis in BRICS economies. Overall, the results support the view that effects vary across the distribution of environmental sustainability, calling for quantile-specific policy approaches. For this purpose, the governments of BRICS countries should focus on increasing renewable energy capacity and introducing feed-in tariff and tax subsidy mechanisms for renewable energy sources, investing in energy storage and smart grid technology, and gradually phasing out fossil fuel subsidies and redirecting the saved resources to renewable energy projects. Green technologies, the circular economy, and resource efficiency should be the focus of technological innovation policies, with governments tying R&D funding to environmental outcomes and encouraging eco-friendly patents and cleaner production

processes. Natural resource revenues should be invested in sustainability initiatives, including renewable energy, land restoration and reforestation, and the bolstering of institutional frameworks, transparency, and environmental regulations to convert resource rents into sustainable sources of development. To reduce environmental damage caused by trade, environmental policies should be integrated into trade agreements, carbon border adjustments should be introduced, low-carbon logistics modes should be encouraged, and stronger environmental governance of export industries should be implemented. Further, BRICS economies should aim for green industrial upgrading, introduce environmental impact assessments, and invest in green infrastructure, public transport, and energy-efficient urban planning, thereby helping achieve economic growth while reducing environmental impact. Lastly, further cooperation among the regions through coordinated climate action, joint green financing and technology-sharing platforms, along with stronger institutional quality and regulatory enforcement, is crucial to ensuring long-term environmental sustainability in the BRICS economies.

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