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Investigating the Relationship between Energy Consumption and Environmental Degradation with the Moderating Influence of Technological Innovation

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Abstract: Energy consumption (ECON) in BRICS countries is fueled by fossil fuels, mainly coal. Increased environmental degradation (ED) in BRICS countries is mostly driven by coal consumption. This study utilizes quantile regression for the analysis, enabling the development of targeted energy reorganization and emission reduction policies in BRICS countries. This study uses data spanning from 1990 to 2022 to explore the impact of ECON on ED. Additionally, technological innovation was used to create a moderating role in the nexus between ECON and ED. The model focuses on CO_2 emissions and the ecological footprint across ten BRICS countries. Among the nations included in the panel, the results indicate a significant dependence on cross-sectional factors. The study shows that ECON has a detrimental impact on ED across all quantiles. However, technological innovation reduces ED. In terms of a moderating role, technological innovation mitigates the negative influence of ECON on ED. Therefore, it is necessary to implement distinct policies in order to accomplish carbon emission reduction goals in various countries.

Keywords: energy consumption; environmental degradation; technological innovation; BRICS; quantile regression

JEL Classification: C33; Q41; Q53; Q55

1. Introduction

In recent years, there has been a consistent rise in concerns around warming temperatures and particular natural ecological disasters (Farooq et al. 2024; Wang et al. 2023, 2024). Hence, the initial and most important approach to address climate damage is emissions of greenhouse gas abatement, which can only be achieved by regulating and decreasing CO_2 emissions and the ecological footprint (Adebayo et al. 2023b; Khattak and Ahmad 2022). The escalating universal warming poses a persistent obstacle to the process of sustainable development due to the excessive squandering and utilization of energy, as well as the inappropriate use of natural resources. Energy is considered both a significant driver of economic growth and the primary factor responsible for ecological harm (Athari 2024). As the manufacturing sector has grown, there has been a significant increase in environmental

CO_2 emissions. However, technological innovation (TECH) is central to falling emissions and attaining energy efficiency at the same time (Işık et al. 2024; Yang et al. 2024). Moreover, TECH plays a vital role in maximizing the utilization of both traditional and renewable energy supplies, thereby reducing CO_2 emissions (Shahbaz et al. 2020). Understanding the factors behind the increase in environmental degradation and determining effective methods to reduce them is crucial for all countries. However, this issue holds particular significance for BRICS nations due to their rapid economic growth and significant contribution to the global economy (Ganda 2024). In light of the SDGs, it is necessary to investigate how TECH influences the relationship between ECON in BRICS nations.

CO_2 emissions resulting from human activity have become a major factor in the occurrence of global warming, accounting for over 77% of total greenhouse gas emissions worldwide. Being the greatest emerging economies globally, BRICS nations have experienced a significant surge in environmental degradation. Another important topic pertains to the specific energy source employed. Coal is the primary source of carbon emissions related to energy production and a significant factor in climate change and the degradation of the environment (Karim et al. 2021; Wen et al. 2024). The utilization of this resource for manufacturing and energy consumption (ECON) leads to substantial ecological and socioeconomic challenges. It exerts a noteworthy impact on worldwide emissions and the promotion of sustainable development (Moussa et al. 2022). TECH significantly influences the levels of environmental degradation. By fostering TECH, nations can provide opportunities to enhance efficiency in sectors that have detrimental impacts on environmental quality while simultaneously improving energy efficiency and reducing ECON. Technology innovation refers to the development and implementation of novel or improved technologies, instruments, structures, and processes that result in notable progress or major breakthroughs across various domains. In addition, nations can gain advantages from technical advancements in enhancing the utilization of existing energy resources (Anwar et al. 2023; Mintah and Elmarzouky 2024). Consequently, it is seen as the fundamental aspect of the shift towards an economy with fewer greenhouse gases.

The industrial sector receives FDI and money from developed nations at the same time as the host country. One perspective asserts that the establishment of industries with the help of FDI leads to a reduction in production costs and creates numerous job opportunities for a significant portion of the population (Lee and Zhao 2023). It also leads to advancements in agricultural inputs and machinery. Conversely, another perspective highlights the detrimental effects of industrialization on the environment, such as pollution and depletion of natural resources (Alkaraan et al. 2023). In recent years, there has been a global expansion of large-scale urbanization movements. Developing countries have a crucial role in driving global urbanization. Urbanization has excessively depleted ecological resources and severely harmed the eco-environment (Nazir et al. 2023; Yang et al. 2024).

Several ecological studies have emphasized the need to restrict pollution in order to attain the Sustainable Development Goals (SDGs) and the goals set by the COP-21 agreement, as it constitutes the greatest percentage of CO_2 emissions. Emerging countries have experienced a significant increase in economic growth in recent times. Conversely, there has been a simultaneous rise in environmental degradation in these countries. Moreover, these nations have a substantial level of ECON. Moreover, these countries exhibit a substantial economic magnitude and have elevated economic expansion (BP 2022). Therefore, it is important to prioritize attention on rising country groups like BRICS, which are responsible for substantial CO_2 emissions, consume large amounts of energy, and enjoy rapid economic growth. This focus can be beneficial not only for these countries themselves but also for other emerging nations that can learn from their experiences.

The specific rationale for selecting BRICS economies is that these nations have shown a shared dedication to promoting sustainable development in their particular regions in spite of ED. Their endeavors comprise projects targeted at promoting infrastructural development and preserving the environment. BRICS countries' major ECON systems continue to be predominantly reliant on fossil fuels, particularly coal, due to differences in economic growth, technology, and energy resources. Both India and China are the primary and secondary major consumers of coal worldwide among BRICS countries, according to the World Bank (2023). Over the past few decades, the BRICS countries, representing 45.38% of the world's population, have seen fast urbanization, economic growth, and industrialization. These factors have resulted in higher levels of carbon emissions. The BRICS countries' high productivity results in a rise in industrial output, which in turn leads to an increase in the extraction of resources and energy consumption. The increase in production activities has a substantial impact on the environment by causing increased pollution and waste production. Despite being among the most rapidly developing nations in the entire globe, the BRICS countries are also the most significant contributors to emissions of carbon dioxide. The combined CO_2 emissions from BRICS countries represent 47.8% of the total global carbon emissions. However, countries continue to generate a significant quantity of CO_2 emissions as a result of their economic structures. Figure 1 illustrates the proportion of the CO_2 emissions, GDP, and the global population within the BRICS countries.

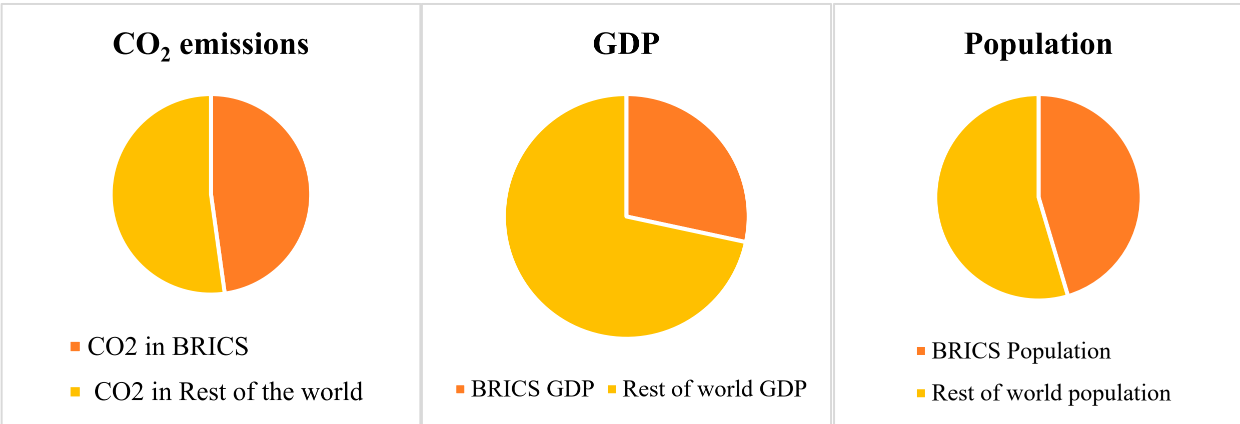

Figure 1. CO_2 emissions, GDP, and Population trend in BRICS Economies. Source: Authors' work (WDI data).

The objective of this study is to examine how TECH affects the connection between ECON and environmental degradation in the BRICS countries. The aim is to contribute to the achievement of the objectives of sustainable development. This study examines the influence of ECON on environmental degradation in 10 BRICS nations from 1990 to 2022. It also explores the moderating effect of TECH. The research methodology employed quantile regression (QR). Furthermore, it examines the various impacts of ECON on carbon dioxide emissions in all quantiles from the 25th to the 90th. This study discovered that TECH has a moderating effect on the adverse consequences of consuming energy on ED.

This work makes significant contributions to the current literature. First, to the best of the authors' knowledge, this is the first study to inspect the connection between environmental degradation and ECON across a panel of all 10 BRICS nations. An analysis of CO_2 emissions and the ecological footprint of coal and its contributing elements can assist each nation in developing tailored coal use policies and implementing necessary measures to facilitate reductions in environmental degradation. Second, this study intends to examine how TECH affects the link amid ECON and environmental degradation. Furthermore, this study conducts a country-based analysis instead of a panel analysis. This decision was made because even though the included nations belong to the same group of nations, there may still be variations among them. Third, this study utilized advanced econometric techniques of the second generation to overcome various methodological challenges, including endogeneity, normalcy, and the capacity to capture a wider range of variances compared to traditional statistical methods. Furthermore, second-generation approaches are considered to be sophisticated, credible, and dependable in treating panel data, particularly where there is heterogeneity and cross-sectional dependency. Finally, the study's conclusions provide appropriate policy possibilities for the economies of the BRICS countries.

The structure of the paper remaining: Section 2 covers the literature on environmental degradation, ECON, and TECH. Section 3 is about research materials, methods, and data sources. Sections 4 and 5 discuss empirical findings and discussion. Section 5 concludes this analysis and discusses policy implications.

2. Literature Review

2.1. Energy Consumption and Environmental Degradation

Carbon emissions and ecological footprint from energy usage are the main causes of global warming and environmental deterioration (Adebayo et al. 2023a). The production and consumption of energy generate serious environmental and socioeconomic issues and affect global carbon emissions and equitable growth. Many countries prioritize socioeconomic development, but warming temperatures and climatic change have shifted attention to energy usage. Many studies have examined the ECON in BRICS nations (Adedoyin et al. 2020; Koilakou et al. 2024; Wen et al. 2024). Adeleye et al. (2021) analyzed a dataset consisting of seven South Asian nations from 1990 to 2019. They employed three empirical methodologies to demonstrate that economic expansion and the usage of nonrenewable energy sources contribute to increased carbon emissions. In contrast, the utilization of renewable energy sources has a mitigating effect on emissions. Nguyen and Kakinaka (2019) utilized panel cointegration techniques to analyze data from 107 countries spanning the years 1990 to 2013. Their findings demonstrate that the use of renewable energy effectively mitigates carbon emissions in countries with high income levels. Chen et al. (2019) examined the ECON and CO_2 reductions in China, the US, and India, which are the biggest three coal users and emitters. However, both researchers employed energy consumption instead of coal usage to calculate CO_2 emissions. Adebayo (2022) used 1990–2018 data to analyze the energy-growth-emissions nexus in Spain and found that energy and economic growth are driving CO_2 emissions. In their analysis of the energy-growth-emission relationship utilizing 1990–2018 data and the dual adjustment approach, Akadiri et al. (2023) found that reducing economic growth and fossil fuel use can achieve environmental sustainability. Gyamfi et al. (2022) found that limiting energy development and economic growth in Mediterranean states from 1990 to 2018 could improve environmental quality. Adebayo et al. (2022) found that fossil fuel and economic enlargement increase CO_2 emissions, triggering ecological harm, using the 1980Q1-2018 time-frequency and dataset for Portugal. Based on the aforementioned findings, we can hypothesize that:

H1: *There is a positive and significant relationship between ECON and ED.*

2.2. Technological Innovation and Energy Consumption

The literature addresses how TECH affects energy demand. Technology that improves energy efficiency reduces ECON and carbon emissions in the Malaysian industry (Li and Solaymani 2021). Few studies have examined the indirect connection between TECH and energy demand through other variables. TECH provides consumers with additional evidence, enabling them to attain a precise understanding and surveillance of the economy (Chui et al. 2018). According to Meinrenken et al. (2020), TECH facilitates the advancement of energy exchange and the management of carbon footprints. Uddin et al. (2022) employed threshold regression to observe the role of financial development in the TECH-ECON nexus in 23 European Union countries. Their findings show that the growth of stock markets, banking industry development, and overall financial development affect energy demand in these countries depending on TECH. TECH's influence on ECON has been divided into both beneficial and detrimental effects. Between 1978 and 1995, TECH in sectors caused most of the decline in energy output ratio in China, and energy product imports also reduced ECON (Garbaccio et al. 1999). Nevertheless, Chen et al. (2021) revealed that TECH improves energy efficiency, which raises energy demand. Adebayo et al.

(2023a), Khan et al. (2022), Sharma et al. (2021), and others have studied the TECH-ECON nexus in BRICS countries. They evaluated the direct influence of TECH on ECON, while our study examined both the direct and indirect effects to better comprehend this nexus. For instance, Sharma et al. (2021) chose to determine if total, vertical, and horizontal export growth in the BRICS countries increased renewable energy demand from 1990 to 2018. The elasticity coefficients showed that diversifying traditional exports of goods, technological innovation, and funding increased cleaner energy use, while new product exports and income inequality decreased it. Khan et al. (2022) examined how ICT, renewable energy, and innovation affected carbon dioxide emissions in BRICS nations from 1990 to 2019 utilizing generalized least squares and panel corrected standard errors models. In the presence of ICT indicators, innovation and renewable energy use significantly reduce emissions. This study uses external and openness to trade as moderators for indirect analysis. Based on the aforementioned findings, we can hypothesize that:

H2: *There is a negative and significant relationship between TECH and ECON.*

2.3. Technological Innovation and Environmental Degradation

TECH prospects have raised academic research and administrative personnel interest on a large scale. Innovation can inspire businesses to ditch old methods and adopt technology. This can create effective green chains and lower pollution (Köksal et al. 2021). Researchers have found that decarburization depends on sustainable energy production and use. Between 1991 and 2016, systematically modified momentary and regression analytical techniques were used to evaluate 103 countries with different economic levels (Yang and Ni 2022). The outcomes showed that TECH is essential in reducing carbon emissions. For developing nations, catching up with the world without emissions is difficult. The overwhelming evidence suggests that the use of technology is essential to lowering CO_2 emissions. Chen and Lei (2018) found that TECH can reduce pollutants and improve the environment. Mensah et al. (2018) used the FMOLS method to study 28 OECD nations from 1990 to 2014 and found that TECH is crucial to CO_2 emission reduction. Hashmi and Alam (2019) used GMM to investigate 29 OECD nations from 1999 to 2014 and found that environmentally friendly patents increased environmental degradation less.

Khattak et al. (2020) used the CCEMG approach to analyze BRICS countries from 1980 to 2016 and found a two-way causality. Shahbaz et al. (2020) used Bootstrapping ARDL to study China from 1984 to 2018 and found that TECH had a decreasing impact on CO_2 emissions. Chen et al. (2022) found that TECH can lessen CO_2 emissions by increasing energy efficiency and green economic output. Saliba et al. (2022) found that TECH reduces long-term CO_2 emissions in China. Chen et al. (2023b) discovered that environmental breakthroughs and patents boost BRICS green development over time. Adebayo et al. (2022) used Morlet wavelet analysis to show that TECH increased emissions of CO_2 in Portugal from 1980 to 2019. Obobisa et al. (2022) employed AMG and CCEMG estimators to analyze data from 25 African nations from 2000–2018. Usman and Radulescu (2022) utilized the same estimators to examine data from the top nine nuclear energy-producing nations between 1990 and 2019. Udeagha and Ngepah (2023) focused specifically on South Africa. Based on the aforementioned findings, we can hypothesize that:

H3: *There is a negative and significant relationship between TECH and ED.*

2.4. Research Gap

A significant body of scholarship has primarily concentrated on the six BRICS economies; however, there is a lack of analysis of the relationship between ED and the economy, particularly with the inclusion of newly joined members. Prior research has primarily focused on a single aspect of environmental degradation (ED); however, this study examines two elements of ED, specifically the release of CO_2 and ecological footprint. In addition, past research has not adequately investigated how TECH acts as a moderator in influencing the relationship between the economy and environmental deterioration.

3. Methodology

This study centers on the 10 emerging economies of BRICS countries, namely Brazil, Russia, India, China, South Africa, Ethiopia, Egypt, Iran, UAE, and Saudi Arabia, from 1990 to 2022. The BRICS countries have added six new countries to their collaboration, with their formal participation slated for 2024. The expansion highlights the BRICS platform's rising relevance in promoting international cooperation for sustainable development. This study determines the optimal sample size and duration based on the availability of data. The data regarding the researched variables, such as CO_2 emissions, ecological footprint, ECON, TECH, economic growth, FDI, urbanization, and natural resources, were gathered from the World Bank (2023), OECD (2023), and QoG (2023), much like in previous publications. Table 1 provides detailed explanations of these factors.

Table 1. Description of the Variables.

Variable	Measurement	Source
CO_2 emissions	Metric tons per capita	World Bank
Ecological footprint	Total ecological footprint of consumption per person (gha per person)	QoG Institute
Energy consumption	Energy use (kg of oil equivalent per capita)	World Bank
Technological Innovation	All technologies (total number of patents)	OECD
Economic growth	GDP growth (annual %)	World Bank
Foreign direct investment	Net inflows (% of GDP)	World Bank
Urbanization	Urban population growth (annual %)	World Bank
Natural resources	Total natural resources rents (% of GDP)	World Bank

Source: Previous studies.

Equation (1) is employed to inspect the effects of ECON on ED by taking its two proxies, namely CO_2 emissions and ecological footprint (ECFT), while the role of TECH is taken as a moderator variable. The functional form of the model is as follows:

$$\mathrm{ED} = \mathrm{f}(\mathrm{ECON},\ \mathrm{TECH},\ \mathrm{Control\ variables}) \tag{1}$$

Equation (1) can be written in econometric form as:

$$\mathrm{CO}_{2\mathrm{it}} = \alpha_0 + \alpha_1\mathrm{ECON}_{\mathrm{it}} + \alpha_2\mathrm{TECH}_{\mathrm{it}} + \alpha_3\mathrm{GDP}_{\mathrm{it}} + \alpha_4\mathrm{FDI}_{\mathrm{it}} + \alpha_5\mathrm{URB}_{\mathrm{it}} + \alpha_6\mathrm{NR}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{2}$$

$$\mathrm{ECFT}_{\mathrm{it}} = \beta_0 + \beta_1\mathrm{ECON}_{\mathrm{it}} + \beta_2\mathrm{TECH}_{\mathrm{it}} + \beta_3\mathrm{GDP}_{\mathrm{it}} + \beta_4\mathrm{FDI}_{\mathrm{it}} + \beta_5\mathrm{URB}_{\mathrm{it}} + \beta_6\mathrm{NR}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{3}$$

where i denotes the country, and t denotes the time period. The term "ε" represents an independent error term. CO_2 emissions and ECFT are taken as dependent variables. ECON pertains to energy consumption, which is taken as the independent variable. TECH represents advancements in technology. GDP, FDI, URB, and NR signify economic growth, foreign direct investment, urbanization, and natural resource rent. Equations (4) and (5) represent the moderating role of TECH.

$$\mathrm{CO}_{2\mathrm{it}} = \alpha_0 + \alpha_1\mathrm{ECON}_{\mathrm{it}} + \alpha_2\mathrm{TECH}_{\mathrm{it}} + \alpha_3\mathrm{ECON}_{\mathrm{it}} \times \mathrm{TECH}_{\mathrm{it}} + \alpha_4\mathrm{GDP}_{\mathrm{it}} + \alpha_5\mathrm{FDI}_{\mathrm{it}} + \alpha_6\mathrm{URB}_{\mathrm{it}} + \alpha_7\mathrm{NR}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{4}$$

$$\mathrm{ECFT}_{\mathrm{it}} = \beta_0 + \beta_1\mathrm{ECON}_{\mathrm{it}} + \beta_2\mathrm{TECH}_{\mathrm{it}} + \beta_3\mathrm{ECON}_{\mathrm{it}} \times \mathrm{TECH}_{\mathrm{it}} + \beta_4\mathrm{GDP}_{\mathrm{it}} + \beta_5\mathrm{FDI}_{\mathrm{it}} + \beta_6\mathrm{URB}_{\mathrm{it}} + \beta_7\mathrm{NR}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{5}$$

Econometric Methods

We employed the Pesaran and Yamagata (2008) method to ascertain if the slope coefficients are homogenous or heterogeneous, as this knowledge can impact regression analysis and mislead hypothesis testing. To determine cross-sectional dependence (C-SD), the Pesaran (2007) C-SD test was used to analyze association coefficients between time-series data for each country. To address the influence of C-SD and slope heterogeneity

(SH) on typical panel unit root testing, we used the Pesaran (2007) test for unit root in the second generation. This method uses t-statistics for panel roots, utilizing the CIPS test for cross-sectional units and the CADF unit root test for average units. The cointegration procedure commences once the stationarity of the parameters is confirmed through first differencing. This method enables us to determine whether there are enduring relationships among the parameters, indicating that the parameters change together over an extended period. Panel cointegration may be used to examine the long-term relationship among the variables. Consequently, we employed cointegration methodologies as outlined in the Westerlund (2008) study. The main benefit of the Westerlund (2008) approach, which is a more advanced method compared to earlier tests, is the fact that it takes into account both C-SD and SH. Further, we create a QR model:

$$ED_{it} = \gamma_\theta + \varepsilon_{it};\ Quant_\theta \langle ED_{it} | X_{it} \rangle = \gamma_\theta \acute{X}_{it} \quad (6)$$

where X is a vector of regressors, ε is a residual vector, and $Quant_\theta \langle ED_{it} | X_{it} \rangle$ represents the θth conditional quantile of ED given X. Figure 2 illustrates the sequence of steps in the analytical process.

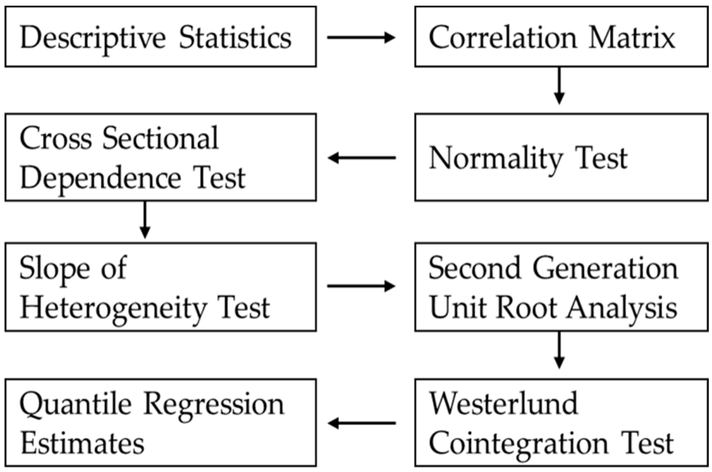

Figure 2. Flow of Analysis, Source: Authors' work.

Koenker and Bassett (1978) established the notion of QR. The QR framework analyzes the influence of a covariate on the dependent variable's conditional variance distribution. The OLS approach evaluates its effect on the conditioned mean of the dependent variable. The majority of the economic parameters in econometric theory exhibit outliers and non-normal patterns (Lin and Xu 2018). Thus, OLS estimates may be inaccurate. QR estimation tolerates outliers and non-normal distributions (Koenker and Bassett 1978). Therefore, QR is better than OLS. The QR framework does not require the standard OLS assumptions, including a null mean, persistent variance, and a normal distribution of residuals (Lin and Xu 2018). Dissimilar to the OLS, which minimizes the residual sum of squares, a QR model adheres to an aim.

We employ three methodological methods to evaluate the QR. Initially, we employ the instantaneous bootstrapped QR technique. This method simultaneously obtains estimations of the covariates across numerous quantiles and generates associated standard errors using a bootstrap methodology. Next, we apply the QR method to analyze clustered data. This approach is both heteroskedastic-robust and capable of producing consistent estimates even when there is an intra-cluster correlation. When sampling data from various units, it is critical to consider intra-cluster correlation. Finally, we employ the generalized QR technique as proposed by Powell (2020). The method uses an instrumental variable approach to address potential problems of endogeneity. In contrast to the first two approaches, the generalized QR method considers a non-additive fixed effect presented by Powell (2022). The non-additive fixed effect guarantees that the error term cannot be separated and allows for parameter modifications. The utilization of the generalized QR approach enhances the accuracy of QR estimates. This strategy yields consistent estimates in panels with a small number of observations and is straightforward to implement.

4. Results

To begin, Table 2 displays the mean, extreme high and low, and standard deviation values of selected variables. This information provides insight into the environmental and economic impact of factors in the assessment model. We measure an average value or central tendency of underlying variables using the mean or average. The standard deviation provides the mean variation or degree of dispersion from the average. The maximum and minimum values of variables are estimated to explain their limitations and range. CO_2 emissions average 7.259, with a standard deviation of 7.363. The average ECFT is 3.607, with a standard deviation of 2.969. The average ECON is 7.494, with a standard deviation of 1.002. The average TECH is 5.828, with a standard deviation of 3.018. Economic growth, FDI, urbanization, and natural resource average 4.249, 1.817, 2.754, and 13.445, with standard deviations of 4.610, 1.733, 2.139, and 11.657, respectively. Table 3 provides the information regarding correlation analysis.

Table 2. Descriptive Statistics.

Variable	Obs.	Mean	Std. Dev.	Min	Max
CO_2 Emissions	330	7.259	7.363	0.029	30.882
Ecological Footprint	330	3.607	2.969	0.680	13.859
Energy Consumption	330	7.494	1.002	5.861	9.367
Technological Innovation	330	5.828	3.018	−1.386	11.503
Economic Growth	330	4.249	4.610	−14.531	18.328
FDI	330	1.817	1.733	−1.776	9.678
Urbanization	330	2.754	2.139	−0.467	18.581
Natural Resources	330	13.445	11.657	0.864	55.024

Source: Authors' own estimation.

Table 3. Correlation Matrix.

	CO_2	ECFT	ECON	TECH	GDP	FDI	URB	NR
CO_2	1.000							
ECFT	0.964	1.000						
ECON	0.993	0.968	1.000					
TECH	−0.026	−0.024	−0.068	1.000				
GDP	−0.129	−0.153	−0.158	0.189	1.000			
FDI	−0.107	−0.029	−0.103	0.167	0.254	1.000		
URB	0.184	0.207	0.169	−0.081	0.239	0.038	1.000	
NR	0.452	0.333	0.471	−0.265	0.030	−0.203	0.220	1.000

Source: Authors' own estimation.

Table 4 provides the normality results; the pattern of distribution of the statistic appears to be not normal. Due to the limitations of conventional empirical estimates in handling irregular data, this study utilized an efficient predictor that statistically analyzes long-term outcomes by addressing irregularities in variables.

Panel data estimation research shows that most environmental economics academics focus on C-SD. Numerous investigations indicate that ignoring the C-SD leads to erroneous outcomes (Phillips and Sul 2003). The statistics confirm C-SD and disprove cross-sectional independence (Table 5). It is clear how something happening in one sample country could affect others. Table 6 provides the findings of the SH test, indicating the heterogeneous slope coefficients.

Table 4. Tests for Normality.

	Skewness and Kurtosis Joint Test		JB Test	
Variable	**Adj $Chi^2(2)$**	**Prob > Chi^2**	**$Chi^2(2)$**	**Prob > Chi^2**
CO_2 Emissions	61.11	0.000	138.2	0.000
Ecological Footprint	79.61	0.000	228.9	0.000
Energy Consumption	146.49	0.000	20.71	0.000
Technological Innovation	10.78	0.000	6.594	0.037
Economic Growth	16.15	0.000	28.71	0.000
FDI	57.83	0.000	147.1	0.000
Urbanization	193.91	0.000	5512	0.000
Natural Resources	41.71	0.000	74.88	0.000

Source: Authors' own estimation.

Table 5. Cross-Sectional Dependence Test.

Variable	CD-Test	*p*-Value
CO_2 Emissions	13.09 ***	0.000
Ecological Footprint	4.39 ***	0.000
Energy Consumption	16.91 ***	0.000
Technological Innovation	26.13 ***	0.000
Economic Growth	7.18 ***	0.000
FDI	7.51 ***	0.000
Urbanization	11.96 ***	0.000
Natural Resources	17.26 ***	0.000

Note: "*** $p < 0.01$". Source: Authors' own estimation.

Table 6. Slope of Heterogeneity Test.

Slope of Heterogeneity	Statistics	*p*-Value
Delta	7.524 ***	0.000
Delta Adjusted	8.823 ***	0.000
Delta $_{(HAC)}$	17.405 ***	0.000
Delta $_{(HAC)}$ Adjusted	20.409 ***	0.000

Note: "*** $p < 0.01$". Source: Authors' own estimation.

After confirming the presence of C-SD and SH, recent research has shown that techniques for testing unit roots in first-generation models are not suitable for determining the level of stationarity in variables. Instead, they recommend using second-generation techniques for unit root testing when dealing with C-SD (Gyamfi et al. 2022). Table 7 displays the outcomes of the CIPS and CADF tests for unit roots: some variables are at the level, and some are at the first differential form. The overall outcomes suggest that all variables demonstrate stationary behavior in their first difference form. Table 8 offers the outcomes of the Westerlund test, indicating that these findings contribute to the existing evidence from cointegration, providing evidence in favor of the variables' long-term association.

ECON has diverse effects on the proxies of environmental degradation, as shown in Tables 9–12. The simultaneous quantile regression results in Tables 9 and 10 indicate that ECON coefficients are significantly higher and positive in the 25th–90th quantiles. A 1% rise in ECON led to a 7.537%, 0.665%, 6.908%, 7.401%, 8.074%, and 8.890% increase in CO_2 emissions and 3.099%, 0.433%, 2.683%, 3.133%, 3.504%, and 3.852% in ECFT, respectively, from the 25th to 90th quantile. In all quantiles (25th–90th), the coefficients for the ECON and TECH variables are positive, as well as significant at the 1% level. Moreover, 1% increases in TECH led to 0.439%, 0.188%, 0.261%, 0.401%, 0.591%, and 0.822% decreases in CO_2 emissions from the 25th to 90th quantile. The results showed that TECH has a negative impact on ED in BRICS countries.

Table 7. Second-Generation Unit Root Analysis.

Variable	CADF		CIPS	
	At Level	At 1st Diff.	At Level	At 1st Diff.
CO_2 Emissions	−1.744	−3.190 ***	−1.428	−4.321 ***
Ecological Footprint	−2.213	−3.868 ***	−2.112	−5.316 ***
Energy Consumption	−3.677 ***	−4.206 ***	−3.530 ***	−4.928 ***
Technological Innovation	−1.921	−3.941 ***	−2.368	−5.406 ***
Economic Growth	−3.641 ***	−4.686 ***	−4.505 ***	−6.384 ***
FDI	−2.863 **	−4.031 ***	−2.899 **	−5.383 ***
Urbanization	−2.961 **	−4.316 ***	−1.984	−4.287 ***
Natural Resources	−2.617	−4.197 ***	−3.141 **	−5.934 ***

Note: "*** $p < 0.01$, ** $p < 0.05$". Source: Authors' own estimation.

Table 8. Westerlund-Durbin-Hausman Cointegration Test.

Statistic	Statistic	*p*-Value
Darbin-Hausman group statistic	2.564	0.000 ***
Darbin-Hausman panel statictic	1.689	0.003 ***

Note: "*** $p < 0.01$". Source: Authors' own estimation.

Table 9. Quantile Regression Estimates for CO_2 Emissions.

Dependent Variable: CO_2 Emissions			Quantiles			
Variables	Location	Scale	Qtile-25	Qtile-50	Qtile-75	Qtile-90
Energy Consumption	7.537 ***	0.665 ***	6.908 ***	7.401 ***	8.074 ***	8.890 ***
	(0.284)	(0.207)	(0.259)	(0.267)	(0.401)	(0.586)
Technological Innovation	−0.439 ***	−0.188 ***	−0.261 ***	−0.401 ***	−0.591 ***	−0.822 ***
	(0.085)	(0.062)	(0.078)	(0.080)	(0.120)	(0.177)
Economic Growth	0.161 ***	0.036	0.127 ***	0.153 ***	0.190 ***	0.233 **
	(0.044)	(0.032)	(0.041)	(0.042)	(0.060)	(0.093)
FDI	−0.037	0.167 **	0.121	−0.003	−0.172	0.378 *
	(0.093)	(0.068)	(0.086)	(0.088)	(0.129)	(0.195)
Urbanization	0.496 ***	0.084	0.417 ***	0.479 ***	0.564 ***	0.666 **
	(0.128)	(0.093)	(0.120)	(0.121)	(0.175)	(0.270)
Natural Resources	−0.091 ***	−0.058 ***	−0.036*	−0.079 ***	−0.137 ***	−0.208 ***
	(0.022)	(0.016)	(0.020)	(0.020)	(0.031)	(0.044)
Constant	−47.427 ***	−1.273	−46.223 ***	−47.166 ***	−48.454 ***	−50.016 ***
	(1.788)	(1.304)	(1.669)	(1.686)	(2.447)	(3.762)
Observations	330	330	330	330	330	330

Note: Standard errors in parenthesis. "*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$". Source: Authors' own estimation.

Table 10. Quantile Regression Estimates for Ecological Footprint.

Dependent Variable: Ecological Footprint			Quantiles			
Variables	Location	Scale	Qtile-25	Qtile-50	Qtile-75	Qtile-90
Energy Consumption	3.099 ***	0.433	2.683 ***	3.133 ***	3.504 ***	3.852 ***
	(0.399)	(0.361)	(0.152)	(0.386)	(0.648)	(0.907)
Technological Innovation	−0.193 *	−0.091	−0.106 **	−0.200 *	−0.278	−0.351
	(0.114)	(0.103)	(0.043)	(0.115)	(0.195)	(0.272)
Economic Growth	0.036	0.030	0.007	0.038	0.064	0.088
	(0.060)	(0.054)	(0.023)	(0.063)	(0.106)	(0.148)
FDI	0.098	−0.077	0.172 ***	0.092	0.026	−0.035
	(0.126)	(0.114)	(0.048)	(0.131)	(0.222)	(0.310)
Urbanization	0.275 *	0.012	0.264 ***	0.276 *	0.286	0.295
	(0.156)	(0.141)	(0.060)	(0.167)	(0.283)	(0.394)

Table 10. *Cont.*

Dependent Variable: Ecological Footprint			Quantiles			
Variables	**Location**	**Scale**	**Qtile-25**	**Qtile-50**	**Qtile-75**	**Qtile-90**
Natural Resources	−0.070 ** (0.031)	−0.022 (0.028)	−0.050 *** (0.012)	−0.072 ** (0.032)	−0.091 * (0.054)	−0.108 (0.075)
Constant	−18.632 *** (2.398)	−1.556 (2.171)	−17.137 *** (0.914)	−18.755 *** (2.437)	−20.085 *** (4.118)	−21.335 *** (5.755)
Observations	330	330	330	330	330	330

Note: Standard errors in parenthesis. "*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$". Source: Authors' own estimation.

Table 11. Quantile Regression Estimates with Moderator for CO_2 Emissions.

Dependent Variable: CO_2 Emissions			Quantiles			
Variables	**Location**	**Scale**	**Qtile-25**	**Qtile-50**	**Qtile-75**	**Qtile-90**
Energy Consumption	8.736 *** (0.401)	1.338 *** (0.214)	7.445 *** (0.369)	8.657 *** (0.451)	10.085 *** (0.506)	10.831 *** (0.588)
Technological Innovation	1.548 *** (0.358)	1.146 *** (0.192)	0.442 (0.332)	1.480 *** (0.396)	2.703 *** (0.455)	3.341 *** (0.529)
ECON×TECH (Moderator)	−0.274 *** (0.053)	−0.178 *** (0.028)	−0.102 ** (0.049)	−0.263 *** (0.059)	−0.454 *** (0.067)	−0.553 *** (0.078)
Economic Growth	0.128 *** (0.034)	−0.030 * (0.018)	0.157 *** (0.032)	0.129 *** (0.034)	0.097 ** (0.044)	0.080 (0.052)
FDI	0.029 (0.076)	0.088** (0.041)	0.114 (0.072)	0.035 (0.076)	−0.059 (0.098)	−0.108 (0.114)
Urbanization	0.374 *** (0.065)	−0.107 *** (0.035)	0.478 *** (0.061)	0.381 *** (0.066)	0.266 *** (0.083)	0.207 ** (0.097)
Natural Resources	−0.075 *** (0.019)	−0.020 ** (0.010)	−0.056 *** (0.018)	−0.074 *** (0.019)	−0.096 *** (0.024)	−0.107 *** (0.028)
Constant	−55.784 *** (2.475)	−6.096 *** (1.325)	−49.902 *** (2.304)	−55.424 *** (2.657)	−61.931 *** (3.152)	−65.328 *** (3.669)
Observations	330	330	330	330	330	330

Note: Standard errors in parenthesis. "*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$". Source: Authors' own estimation.

Table 12. Quantile Regression Estimates with Moderator for Ecological Footprint.

Dependent Variable: Ecological Footprint			Quantiles			
Variables	**Location**	**Scale**	**Qtile-25**	**Qtile-50**	**Qtile-75**	**Qtile-90**
Energy Consumption	3.309 *** (0.292)	0.640 *** (0.227)	2.689 *** (0.419)	3.368 *** (0.280)	3.930 *** (0.270)	4.343 *** (0.331)
Technological Innovation	0.154 (0.242)	0.295 (0.189)	−0.132 (0.359)	0.181 (0.234)	0.440 ** (0.225)	0.631 ** (0.283)
ECON×TECH (Moderator)	−0.048 (0.037)	−0.053 * (0.028)	0.003 (0.054)	−0.053 (0.035)	−0.099 *** (0.034)	−0.133 *** (0.043)
Economic Growth	0.030 (0.024)	0.018 (0.019)	0.012 (0.036)	0.032 (0.023)	0.048 ** (0.022)	0.059 ** (0.028)
FDI	0.110 ** (0.052)	−0.057 (0.040)	0.165 ** (0.078)	0.104 ** (0.050)	0.054 (0.048)	0.017 (0.061)
Urbanization	0.254 *** (0.056)	−0.025 (0.044)	0.277 *** (0.085)	0.251 *** (0.055)	0.230 *** (0.052)	0.214 *** (0.067)
Natural Resources	−0.068 *** (0.013)	−0.013 (0.010)	−0.055 *** (0.020)	−0.069 *** (0.013)	−0.081 *** (0.012)	−0.089 *** (0.016)
Constant	−20.092 *** (1.806)	−3.030 ** (1.406)	−17.156 *** (2.627)	−20.371 *** (1.736)	−23.036 *** (1.673)	−24.993 *** (2.075)
Observations	330	330	330	330	330	330

Note: Standard errors in parenthesis. "*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$". Source: Authors' own estimation.

Tables 11 and 12 present the moderating influence of TECH on the relationship between ECON and ED. This indicates that investment in research and development activities in BRICS nations leads to TECH, which in turn promotes the decrease in ECON. This is accomplished by employing energy-efficient equipment and products, hence promoting energy efficiency in BRICS countries. The literature also found negative results and shows that TECH has a substantial impact on reducing energy use. TECH moderates the negative influence of ECON on ED.

Subsequently, the causality analysis examines the relationships between ECON, TECH, CO_2 emissions, ECFT, economic growth, FDI, urbanization, and natural resources (Table 13). The study found a bidirectional relationship between CO_2 emissions, ECFT, ECON, and TECH. Rising carbon emissions and ecological footprints are correlated with energy consumption and TECH in BRICS economies. A one-way causality exists between the remaining variables.

Table 13. Dumitrescu Hurlin Panel Causality Tests.

Null Hypothesis:	W-Stat.	$\bar{Z}$	Prob.
Energy consumption ↛ CO_2 emissions	5.345	8.401	0.000
CO_2 emissions ↛ Energy consumption	5.040	7.802	0.000
Technological innovation ↛ CO_2 emissions	4.539	6.815	0.000
CO_2 emissions ↛ Technological innovation	2.046	1.912	0.056
Economic growth ↛ CO_2 emissions	1.759	1.348	0.178
CO_2 emissions ↛ Economic growth	3.304	4.387	0.000
FDI ↛ CO_2 emissions	1.964	1.751	0.080
CO_2 emissions ↛ FDI	1.809	1.445	0.149
Urbanization ↛ CO_2 emissions	2.003	1.826	0.068
CO_2 emissions ↛ Urbanization	1.095	0.040	0.968
Natural resources ↛ CO_2 emissions	2.247	2.307	0.021
CO_2 emissions ↛ Natural resources	1.579	0.993	0.321
Energy consumption ↛ Ecological footprint	5.684	9.069	0.000
Ecological footprint ↛ Energy consumption	3.375	4.527	0.000
Technological innovation ↛ Ecological footprint	3.675	5.116	0.000
Ecological footprint ↛ Technological innovation	1.979	1.779	0.075
Economic growth ↛ Ecological footprint	2.167	2.150	0.032
Ecological footprint ↛ Economic growth	3.102	3.989	0.000
FDI ↛ Ecological footprint	1.061	−0.026	0.979
Ecological footprint ↛ FDI	2.200	2.214	0.027
Urbanization ↛ Ecological footprint	1.821	1.470	0.142
Ecological footprint ↛ Urbanization	1.185	0.218	0.828
Natural resources ↛ Ecological footprint	0.854	−0.434	0.664
Ecological footprint ↛ Natural resources	1.748	1.325	0.185

Source: Authors' own estimation.

5. Discussion

ECON has various impacts on the indicators of environmental degradation, as demonstrated in Tables 9–12. This discovery offers a compelling indication that renewable energy foundations are more desirable, as they can help reduce emissions. The analysis indicates that ECON has a harmful impact on ED. As industrialized economies, BRICS countries rely heavily on coal, natural gas, and oil for power. Petroleum-based diesel, fossil fuels, petroleum, and other renewables generate electricity. The consumption of fossil fuel power does not promote environmental safety. Adebayo et al. (2023a), Adebayo et al. (2022), Adedoyin et al. (2020), Koilakou et al. (2024), and Wen et al. (2024) found that countries desperately use coal, natural gas, and oil for economic growth, which increases CO_2 emissions and environmental degradation. However, the coefficients for TECH are negative for both CO_2 emissions and ECFT.

The findings indicate that technology has a detrimental effect on economic development in the BRICS countries. Research and development breakthroughs boost firm-level production technologies. Therefore, technology spillovers affect emissions and environmental damage. These results are consistent with studies by Adebayo et al. (2023b), Garbaccio et al. (1999), Li and Solaymani (2021), and Uddin et al. (2022), who emphasized clean and green TECH that improves the environment by dropping CO_2 emissions. Moreover, economic growth and urbanization increase environmental degradation, whereas resource rent has a negative effect, indicating the inverse link between natural resources and environmental degradation. Investment in research and development activities in BRICS nations leads to TECH, which in turn promotes the decrease in ECON. This is achieved through the utilization of energy-efficient equipment and goods, hence supporting the efficiency of energy in BRICS countries. This conclusion aligns with the research conducted by Sharma et al. (2021) using BRICS data. These studies also found negative results and show that TECH has a substantial impact on reducing energy use. TECH moderates the negative influence of ECON on ED.

The positive impact of economic expansion on CO_2 emissions and ECFT suggests that increasing GDP leads to greater environmental degradation. The increase in influence leads to increased interest in commodities and resources, which are often shaped using energy and natural resources. This heightened demand exerts additional pressure on the environment, worsening ecological conditions. The BRICS region has experienced significant economic growth in recent years. This rapid expansion has a negative influence on the ecological setting. These results support prior research (Bunnag 2023; Mirziyoyeva and Salahodjaev 2023; Opoku and Aluko 2021). The outcomes demonstrate the detrimental outcome of FDI on CO_2 emissions and ECFT, indicating a statistically significant impact on economic development in BRICS states. These conclusions align with studies by Khan et al. (2023), Lee and Zhao (2023), and Xie et al. (2020) regarding the relationship between FDI and CO_2 emissions. In terms of urbanization, findings indicate that urban population growth leads to environmental degradation. Rapid population development and urbanization raise environmental pressure through greater energy demand. The findings align with preceding research (Chen et al. 2023a; Mahmood et al. 2020; Zhang et al. 2021). Similarly, natural resource use also contributes to CO_2 emissions.

6. Conclusions

Emerging economies are crucial for global economic development and play a critical role in the global community as a whole. The BRICS nations are among the primary causes of the worldwide increase in CO_2 emissions. Without adjusting their energy architectures, BRICS countries will continue to be the biggest contributors to the world's emissions of carbon dioxide. This study employs a quantile regression approach to explore the diverse impacts of ECON on environmental degradation in 10 BRICS countries from 1990 to 2022. The aim is to gain a deeper understanding of how TECH moderates the link between ECON and environmental degradation in BRICS. In order to fully measure environmental deterioration, we opted to utilize CO_2 emissions and ecological footprint calculations of countries, which are commonly utilized in empirical studies. According to the results of the generalized quantile regression investigation, we observed a positive relationship between CO_2 emissions and ECFT with ECON across all quantiles. This suggests that ECON has a damaging influence on the environment throughout the range. Furthermore, our analysis revealed that TECH has a beneficial impact on environmental quality in all percentiles. This discovery indicates that TECH restricts environmental deterioration. The results of our study confirm the moderating role of TECH in the link between ECON and environmental degradation.

This study developed key policies to help policymakers, energy organizations, and other government officials improve their energy-saving strategies in line with the SDG

Vision 2030. The suggested policies are as follows: The C-SD of variables provisions BRICS countries' common ECON reduction strategies for sustainability. Creating common energy protocols and strategies would encourage research and the progress of energy-efficient TECH and renewable energy infrastructure. BRICS members must ensure investments and enforce regulations, particularly energy-saving policies. Energy-saving incentives and stimulus funds may be implemented to promote enterprises that combine energy-saving and carbon emission reduction. Increase public knowledge of renewable sources of energy and hygienic environments in BRICS countries. The government should develop programs and regulations to promote technologies.

This study is advantageous to society as it emphasizes the pivotal role of technical innovation in alleviating the adverse environmental effects of increased energy use. The research establishes a correlation, enabling regulators and industry executives to prioritize the development and implementation of more environmentally friendly technologies. In order to implement this study, a suggested approach could entail government incentives to promote environmentally friendly innovation, funding for development and research, and collaborations between the public and private sectors with the goal of decreasing carbon emissions while ensuring optimal energy usage.

While this study does offer some valuable insights into the existing literature, it is imperative to note that some specific limitations and considerations should be recognized. These limitations can serve as areas of focus for future research. Future research should conduct a sectoral investigation to identify the specific segments that subsidize CO_2 emissions and determine how to guide energy-effective segments that may be responsible for these emissions if data availability allows. Despite being in its early stages, the application of machine learning techniques derived from artificial intelligence has demonstrated significant effectiveness in related fields.

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Abbreviation

Acronym	Variable
CO_2	CO_2 emissions
ECFT	Ecological footprint
ECON	Energy consumption
TECH	Technological Innovation
GDP	Economic growth
FDI	Foreign direct investment
URB	Urbanization
NR	Natural resources

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