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Unraveling the Dynamics of BRICS: A Comprehensive Analysis of CO2 Emissions, Energy Consumption, and Technological Innovation

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ABSTRACT

With rising worldwide concerns about climate change and environmental sustainability, it is crucial to understand the link between energy usage, technological innovation, and CO2 emissions. Therefore, this study examines the complex link between energy consumption, technological innovation, and CO2 emissions in the BRICS economies over the time period from 1990 to 2022. To understand the BRICS dynamics and environmental sustainability, the Panel Mean Group Autoregressive Distributed Lag (PMG-ARDL) model is used. The results indicate a significant positive relationship between energy consumption and CO2 emissions, implying that BRICS economies experience a rise in CO2 output due to increased energy usage. Simultaneously, the research reveals an inverse connection between technological innovation and CO2 emissions. In this regard, technological advances are crucial for sustainable growth and environmental protection in the region. This research provides useful insights into the intricate interaction of factors that influence CO2 emissions in developing nations.

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1. Introduction

In the early 2000's, the formation of the BRICS concept signified a fundamental change in the forces governing the global economy. At first recognized as anticipating emerging markets, these countries subsequently garnered considerable interest due to their substantial contributions to worldwide economic expansion. Due to their distinct economic capabilities, Brazil, Russia, India, China, and South Africa expanded their spheres of influence at an accelerated rate, emerging as significant participants in global trade and investment. Nevertheless, this economic rise has not been devoid of obstacles, specifically with regard to environmental sustainability (Shan et al., 2021). The BRICS countries' swift industrialization, urban expansion, and infrastructure development have substantially contributed to heightened energy consumption, predominantly powered by fossil fuels. As a consequence of this energy consumption, significant CO2 emissions are produced, which further exacerbates concerns regarding environmental degradation and climate change. The BRICS countries as a group contribute significantly to worldwide carbon emissions, which signifies the ecological consequences of their respective economic development paths (Global Carbon Atlas, 2021).

An in-depth analysis of the data and statistics unveils the magnitude and influence of the BRICS economies on an international level. The BRICS countries exhibited remarkable economic expansion, as evidenced by the substantial increase in their combined GDP from $3.2 trillion in 1990 to more than $22.5 trillion in 2020, as reported by the World Bank (2020). In contrast, this expansion of the economy has been accompanied by an equivalent increase in energy consumption. The BRICS countries accounted for 42% of global energy demand in 2019, according to the IEA (2019). This demand is met mostly by fossil fuels, affecting the global energy landscape. These countries' CO2 emissions have increased significantly over time. In 1990, the BRICS countries' total CO_2 emissions were around 6.2 billion metric tons, according to the Global Carbon Atlas (2021). This amount had increased by almost 100% by 2019, surpassing 17.8 billion metric tons. These numbers show how the BRICS countries' fast economic growth has affected the environment and how important it is to research the connections between technological innovation, energy consumption, and carbon dioxide emissions.

This study was prompted by the BRICS countries' economic success and environmental issues. These economies have pulled millions out of poverty and transformed the global economy, but their environmental impact has been criticized (Hieu & Hai, 2023). Comprehending and striking a balance between the trade-offs of environmental sustainability and economic development constitutes the underlying impetus. The global fight against climate change makes these issues even more urgent. The IPCC assessments and international climate agreements emphasize the importance of big economies, especially the BRICS, in influencing global environmental sustainability. By doing so, this study seeks to contribute to the discourse on sustainable development in the context of the BRICS, with the ultimate goal of informing policy decisions that strike a balance between environmental preservation and economic growth (Rahman & Turay, 2018).

This study is important because it could help us understand the complex connections between CO2 emissions, energy use, and new technologies in the BRICS countries. First, the study fills in a major gap in the research by looking at all of these factors together over a long period of time, from 1990 to 2022. Second, as large emitters and energy consumers, the BRICS economies shape the global climate change response. The knowledge acquired from this research can provide valuable input for global strategies, and cooperative endeavors that seek to alleviate the ecological consequences of economic expansion in developing countries.

Moreover, this study holds great importance in examining the interconnected story of economic progress and ecological preservation in the BRICS countries. The research is designed to clarify the complex interconnections among the above-mentioned variables. Its objective is to provide guidance to policymakers, researchers, and stakeholders in formulating ways that promote sustainable development while maintaining economic progress. The study also considers the BRICS' diversity. Each country has different socio-economic systems, policy agendas, and technical advancement. This diversity is intended to provide a complete and deep knowledge of BRICS economic progress and environmental sustainability.

As the BRICS countries exert their influence globally, it is crucial to examine the complex relationship between carbon dioxide (CO2) emissions, energy consumption, and technological innovation. This study aims to analyze the intricate connections between many factors from 1990 to 2022, with the goal of gaining a deeper understanding of the sustainability landscape in the BRICS setting. The objectives of the study as: First, examine BRICS energy consumption patterns, trends, and factors. Second, analyze the influence of technical innovation on the environmental consequences of economic activity, taking into account both beneficial and detrimental contributions. Third, give meaningful insights for BRICS and global policymakers on sustainable development that balances economic growth and environmental preservation.

The subsequent sections of the paper are structured in the following manner: upcoming section provides the "Review of the literature", "Data and methodology" part outlines the specific methodology used in the analysis. The "Results and discussion" section presents the findings and discussion. The "Conclusion and policy implication" section provides the concluding remarks of the study.

2. Literature Review

Environmental economics literature has focused on energy use and CO2 emissions. Burning non-renewable energy sources like coal, oil, and natural gas has long been linked to CO2 emissions and global warming (Depren et al., 2022). The Environmental Kuznets Curve (EKC) theory, along with other conventional hypotheses, suggests a non-linear link between economic expansion, energy use, and environmental deterioration. It proposes that as economies expand, environmental impact first decreases before eventually improving. The ongoing investigation of the correlation between energy consumption and carbon dioxide (CO2) emissions remains a pivotal field of study. Recent studies emphasize the importance of detailed analysis to understand the changing dynamics (Chen & Lei, 2018; Khattak et al., 2022). Shan et al. (2021) highlighted the detrimental ecological consequences associated with the use of non-renewable energy sources, asserting that substantial volumes of CO2, a prominent greenhouse gas, are discharged into the atmosphere during the combustion of fossil fuels.

Xin et al. (2021) use modern econometric methods to investigate the reciprocal relationship between energy use and CO2 emissions. They propose that comprehending this link requires addressing energy source and policy context heterogeneity. Further, there is a growing recognition of the significance of the shift towards renewable energy sources and the progress made in energy efficiency technologies. The study by Kartal (2022) demonstrates the effect of utilizing renewable energy sources to decrease carbon dioxide (CO2) emissions, suggesting a transition towards a more environmentally sustainable energy framework. The aforementioned results emphasize the criticality of adopting cleaner energy alternatives in order to alleviate the ecological consequences of energy usage.

Innovation in technology continue to be crucial in the effort to reduce CO2 emissions (Khattak et al., 2020). In recent scholarly works, the transformative capacity of innovation in addressing environmental consequences has been noted. Ahmad and Zheng (2021) examine the function of digital technologies, emphasizing the potential for enhanced environmental friendliness and productivity through the implementation of digitalization. This viewpoint broadens the conventional comprehension of technological innovation by integrating the digital aspect into the pursuit of sustainable development. Moreover, the notion of green innovation is becoming increasingly popular. Chen and Lei (2018) highlights the significance of promoting green innovation to achieve sustainable development, offering valuable perspectives on the capacity of innovation to influence the adoption of environmentally conscious practices. This literature is in line with the current trend of promoting environmentally friendly technologies and sustainable economic practices.

Recent literature emphasizes the importance for a comprehensive understanding of energy usage, technological innovation, and CO2 emissions (Ahmad & Zheng, 2021; Chen & Lei, 2018; Khattak et al., 2020). Khan et al. (2022) analyze these variables to find nonlinear correlations and complex feedback processes. This approach mirrors the modern understanding that environmental issues require a coordinated solution that incorporates energy and technology. Moreover, there is an increasing focus on the importance of intelligent technology in attaining objectives related to sustainability (Luo et al., 2021). Song et al. (2022) investigates the influence of smart city technologies on energy usage and CO2 emits, demonstrating the capacity of using advancements in urban development to achieve environmental advantages.

Nurgazina et al. (2022) conducted an extensive analysis within the China and concluded that although economic growth did contribute to higher CO2 emissions. Essandoh et al. (2020) utilize an extensive panel data analysis to examine the influence of foreign direct investment (FDI) on carbon dioxide (CO2) emissions, taking into account the moderating effect of environmental restrictions. Their research offers valuable insights into the complex correlation between foreign investment and environmental consequences. Dogan and Seker (2016) emphasize that trade openness can result in emissions leakage, illustrating the significance of taking into account the worldwide distribution of emissions in the age of interconnected economies. According to the findings of Ang (2007), urbanization is a contributor to increased CO2 emissions, which suggests that there are issues connected with rapid urban expansion.

Few studies have incorporated CO2 emissions, energy consumption, and technological innovation in case of BRICS (Khattak et al., 2020; Santra, 2017; Su et al., 2021). Studies often focus on certain elements or countries within the cluster. Santra (2017) examined these variables' interconnectivity in a comprehensive investigation. The study only covered a short time period, thus more research on long-term dynamics is needed. This literature gap makes the present study unique and important in its attempt to explain the relationship between CO2 emissions, energy consumption, and technological innovation in the BRICS economies from 1990 to 2022. There is another gap that is known as methodological gap. This study will use the Panel ARDL (PMG-ARDL) for the current analysis.

3. Data and Methodology

The main objective of this research is to conduct a thorough analysis of the dynamic relationship among carbon dioxide (CO2) emissions, energy usage, and technological advancements in the BRICS economies spanning the years 1990 to 2022. This period refers to the time after the Cold War, characterized by notable economic changes, technical progress, and increased environmental consciousness among the BRICS countries. The study incorporates the BRICS countries, namely Brazil, Russia, India, China, and South Africa, because of their combined significance in global economic matters. These countries exhibit a wide range of economic structures, levels of technical advancement, and environmental policies, which makes them an ideal group to thoroughly analyze the study variables. The data employed in this analysis is obtained from the World Bank's World Development Indicators (World Bank, 2020). Table 1 presents an overview of the variables.

Table 1
Description of the Variables

Abbreviation	Full Name	Measurement	Data Source
CO2	CO2 emissions	Metric tons per capita	WDI
ENGC	Energy consumption	Kg of oil equivalent per capita	WDI
TECH	Technological Innovation	R & D expenditure (% of GDP)	WDI
GDP	Economic growth	GDP growth (annual %)	WDI
FDI	Foreign direct investment	Net inflows (% of GDP)	WDI
TRD	Trade	% of GDP	WDI
URB	Urbanization	% of total population	WDI

Source: Previous studies

The study utilizes panel data to conduct a comprehensive analysis of both cross-sectional and time-series variances among the BRICS countries. This methodology allows for a more comprehensive examination of the enduring connections between the variables of interest. The study utilizes a dynamic panel data model to examine the correlations among CO2 emissions as dependent variable, energy consumption, technological innovation as independent variables, and economic growth, foreign direct investment (FDI), trade, and urbanization as control variables in order to assess their potential influence on the relationship between the primary variables. The specified model is as follows:

$$CO_2 = f(ENGC, TECH, GDP, FDI, TRD, URB) \quad (1)$$

In econometric form equation (1) can be written as follows:

$$CO_{2it} = \beta_0 + \beta_1 ENGC_{it} + \beta_2 TECH_{it} + \beta_3 GDP_{it} + \beta_4 FDI_{it} + \beta_5 TRD_{it} + \beta_6 URB_{it} + \varepsilon_{it} \quad (2)$$

where CO_2, ENGC, TECH, GDP, FDI, TRD, and URB stands for CO2 emissions, energy consumption, technological innovation, economic growth, foreign direct investment, trade, urbanization respectively. While the subscript i represents countries, and subscript t represents time. The error term ε_{it} accounts for unobserved heterogeneity and potential cross-sectional dependence.

The study applies a variety of econometric methods to produce reliable and solid outcomes. The study employs Pesaran (2004) CD test to check the cross-sectional dependence in the variables. If the CD exists, the study uses second generation unit root tests, such as the CIPS and CADF tests (Pesaran, 2007), to evaluate the stationarity of the variables. In the next step, the Kao (1999) cointegration test is utilized to detect long-term associations between the variables. Finally, the study uses the Panel Autoregressive Distributed Lag (PMG-ARDL) estimation method to look at how the links change over both short and long periods of time. The PMG-ARDL technique is designed for panel datasets with mixed integration orders (Pesaran et al., 1999). This method takes into account the possibility of cross-sectional dependence and variability. PMG-ARDL is a suitable tool for investigating cointegration and long-run relationships among variables in a panel context. PMG-ARDL can handle slopes that vary in nature. By using PMG-ARDL estimation method, the study aims to give a solid and detailed picture of how CO2 emissions, energy use, new technologies, and control variables are linked in the BRICS countries.

4. Results and Discussion

This section represents the descriptive statistics of the variables, correlation analysis, CD test to check the cross-sectional dependence, unit root test for the stationarity, co-integration test to determine the long-run relationship exist or not in the model, and at last the estimation results of PMG-ARDL technique. The descriptive analysis of the study is presented in table 2. The mean value of CO2 emissions is 5.287, while minimum and maximum values are 0.647 and 14.621 (metric ton per capita), respectively in BRICS countries. BRICS countries are emitting a high level of CO2 in air due to industrialization and urbanization. The mean value of energy consumption shows that the BRICS countries are consuming a lot of energy that ultimately becomes the cause of CO2 emissions. The minimum and maximum values are 351.212 and 5941.586 respectively. Moreover, the mean value of technological innovation is 0.990, minimum value is 0.527, and the maximum value is 2.433. The maximum value of TECH shows that BRICS economies are highly investing in research and development to control the pollution. Similarly, the mean, minimum, and maximum values of the GDP, FDI, trade and urbanization are presented in table 2. Table 3 shows the correlation matrix of the variables. The results of CD test are presented in Table 4. The null hypothesis for this test is there is no cross-sectional dependence. If significance level is less than 5%, reject the null hypothesis and accept the alternative hypothesis that is CD exist. As in case of this study, the prob value is less than 0.05, which indicates that the presence of cross-sectional dependence.

Table 2
Descriptive Statistics

Variables	Mean	Max.	Mini.	Std. Dev.	Skewness	Kurtosis
CO2	5.287	14.621	0.647	3.946	0.483	1.884
ENGC	2103.664	5941.586	351.212	1536.926	0.842	2.538
TECH	0.990	2.433	0.527	0.400	1.722	6.060
GDP	3.980	14.231	-14.531	4.744	-0.790	4.543
FDI	2.018	9.678	-1.787	1.577	0.984	5.171
TRD	40.929	110.577	15.156	14.734	0.505	4.586
URB	58.079	87.555	25.547	20.077	-0.293	1.672

Source: Authors' estimation

Table 3
Correlation Analysis

	CO2	ENGC	TECH	GDP	FDI	TRD	URB
CO2	1.000						
ENGC	0.969	1.000					
TECH	-0.240	-0.185	1.000				
GDP	0.342	0.422	0.084	1.000			
FDI	-0.146	-0.138	0.168	0.356	1.000		
TRD	0.648	0.557	0.027	-0.066	0.035	1.000	
URB	0.430	0.545	0.331	-0.509	0.098	0.040	1.000

Source: Authors' estimation

Table 4
Cross-Sectional Dependence Test

Test	Statistic	d.f.	Prob.
Breusch-Pagan LM	44.960	10	0.000
Pesaran scaled LM	6.699		0.000
Pesaran CD	-2.107		0.035

Source: Authors' estimation

According to the findings that CD exists, we need to employ the second-generation unit root test that gives better and reliable results, because in the presence of CD the first-generation unit root test gives the spurious results (Gyamfi et al., 2022). Table 5 shows the second-generation unit test results. We employed the CIPS and CADF to check the stationarity of the variables. The results of the both tests indicates the mixed order of integration that means some variables are stationary at level and some variables becomes stationary after taking the first difference. After confirming the stationarity of the variables, further this study reports the results of co-integration test in table 6. To check the co-integration, Kao (1999) test is used. The value of ADF indicates that variables of the study are co-integrated.

Table 5
Second Generation Unit Root Test

	CIPS		CADF	
Variables	**At Level**	**At 1st Difference**	**At Level**	**At 1st Difference**
CO2	-2.651***	–	-2.838***	–
ENGC	-2.247**	–	-3.141***	–
TECH	-2.053	-4.875***	-2.130	-3.819***
GDP	-3.445***	–	-2.633**	–
FDI	-2.147**	–	-1.764	-3.833***
TRD	-1.938	-4.863***	-2.416*	–
URB	-1.449	-3.174***	-1.823	-3.251***

Source: Authors' estimation

Table 6
Co-integration Test

Test	t-Statistic	Prob.
ADF	-2.756	0.003
Residual variance	0.030	
HAC variance	0.023	

Source: Authors' estimation

The study employed the PMG-ARDL technique to check the impact of energy consumption and technological innovation on CO2 emissions. The results are reported in table 7. The coefficient value of the energy consumption shows that there is a positive relation among the energy consumption and CO2. If the energy consumption is increased by one unit, it can boost the CO2 emissions by 0.238 units in BRICS economies. Since BRICS economies use fossil fuels for energy, their energy consumption increases CO2 emissions (Shan et al., 2021). Burning coal, oil, and natural gas increases carbon dioxide emissions, worsening global warming. Rapid industrialization and urbanization in BRICS nations increase energy consumption and carbon-intensive source use (Kartal et al., 2022). While the negative sign with the coefficient of technology indicates that if technological innovation increased by one percent, it decreases the CO2 emission by 1.959 units. Technological innovation helps BRICS economies reduce CO2 emissions by providing cleaner energy sources and energy efficiency. Solar and wind energy are sustainable alternatives to fossil fuels (Khattak et al., 2020). Energy efficiency is increased by smart grids, energy storage, and industrial processes. Electric automobiles and public transit improvements reduce carbon emissions. Incentives for these technical advances can help BRICS nations transition to a low-carbon, environmentally friendly future (Khattak et al., 2022). These countries must switch to greener energy sources and adopt energy efficiency and carbon reduction strategies to lessen environmental effect.

Table 7
Results of PMG-ARDL

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
		Long Run Equation		
ENGC	0.238	0.107	-2.224	0.027
TECH	-1.959	1.024	-1.913	0.059
GDP	0.202	0.054	3.732	0.000
FDI	-0.085	0.054	-1.577	0.118
TRD	0.089	0.020	4.550	0.000
URB	0.051	0.022	2.318	0.013
		Short Run Equation		
COINTEQ	-0.088	0.043	-2.034	0.044
D(ENGC)	0.106	0.035	3.029	0.003
D(ENGC(-1))	-0.120	0.277	-0.433	0.666
D(TECH)	-0.086	0.198	-0.433	0.666
D(TECH(-1))	-0.541	0.284	-1.902	0.060
D(GDP)	-0.014	0.010	-1.341	0.183
D(GDP(-1))	-0.005	0.005	-1.126	0.263
D(FDI)	0.037	0.023	1.619	0.109
D(FDI(-1))	0.012	0.027	0.435	0.664
D(TRD)	-0.012	0.013	-0.947	0.346
D(TRD(-1))	-0.002	0.008	-0.262	0.794
D(URB)	0.504	0.471	1.070	0.288
D(URB(-1))	2.250	1.843	1.221	0.225
C	-0.359	0.596	-0.601	0.549

Source: Authors' estimation

The results of analysis found that GDP, trade, and urbanization positively and statistically significantly affect CO2 emissions. First, the positive GDP coefficient means CO2 emissions rise with GDP. This shows the difficulty of separating economic expansion from environmental effect (Katrakilidis et al., 2016). Second, the positive and strong association between trade and CO2 emissions shows that more trade increases carbon emissions. International trade may cause environmental problems due to transportation emissions and energy-intensive industry (Dogan & Seker, 2016). Third, the results show that urbanization increases CO2 emissions, with a positive and substantial coefficient. Sustainable urban planning and regulations are needed to reduce the environmental impacts of growing urbanization (Ang, 2007). These findings demonstrate the difficulty of reconciling economic growth with environmental sustainability. The study also provides insights for developing comprehensive strategies that balance economic development and environmental protection in our quickly changing global context.

5. Conclusion and Policy Implications

In conclusion, the comprehensive analysis of CO2 emissions in BRICS economies from 1990 to 2022 reveals a complex interplay of factors shaping environmental sustainability. The negative effect of energy consumption on CO_2 emissions highlights the environmental impacts of conventional and carbon-intensive energy sources. Industrialization in BRICS economies increase the energy demand, which raises CO_2 emissions. This is mostly caused by the use of fossil fuels like coal, oil, and natural gas. These fuels release significant volumes of carbon dioxide, a key greenhouse gas, into the atmosphere, worsening global warming. While the results shows that technological innovation negatively associated with CO_2 emissions. Reduced CO_2 emissions depend on solar, wind, hydropower, and geothermal energy innovation. As these technologies become more efficient and cost-effective, they can replace fossil fuels and reduce carbon emissions. Advanced energy storage technologies like batteries enable more efficient grid integration of intermittent renewable energy sources. Transportation advancements including electric vehicles (EVs), hybrid vehicles, and fuel-efficient engines reduce CO_2 emissions. GDP, trade, and urbanization consistently positively and significantly affect CO_2 emissions in the BRICS economies. This shows how difficult it is for these nations to balance economic growth and environmental sustainability.

CO_2 emissions rise as GDP, trade, and urbanization increase, emphasizing the need for smart and sustainable governmental interventions. Encourage greener and renewable energy use. This may include renewable energy subsidies, tax incentives, and sustainable energy regulations. Need to make and implement green innovation policies. To ensure technological advancement meets environmental sustainability goals, promote green energy, carbon capture, and sustainable agriculture research. Prioritize sustainable urban planning with energy-efficient infrastructure. This can reduce urbanization's environmental impact and make cities greener. Trade policies should consider the environment. Promote eco-friendly trade and technology. These policy recommendations can help BRICS economies balance economic development and environmental protection, creating a sustainable and resilient future for their population and the earth.

Authors Contribution

Muhammad Nouman Shafiq: study design, data analysis & interpretation, drafting
Ali Zafar: literature search, data collection, drafting

Conflict of Interests/Disclosures

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