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RESEARCH ARTICLE

Navigating a Greener Future: The Role of Geopolitical Risk, Financial Inclusion, and AI Innovation in the BRICS – An Empirical Analysis

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Abstract

This study examines the impact of Geopolitical Risk, Financial Inclusion, and AI Innovation on CO_2 emissions in BRICS countries from 2000 to 2019, alongside Renewable Energy Use and Economic Growth. Econometric tests revealed cross-sectional dependence and heterogeneity across the panel, with unit root tests confirming stationarity. A second-generation panel cointegration test established a long-run equilibrium relationship among the variables. Using the Panel Autoregressive Distributed Lag (ARDL) model, the analysis found that GDP and Geopolitical Risk significantly increase CO_2 emissions in both the short and long run. In contrast, AI Innovation, Financial Inclusion, and Renewable Energy Use substantially reduce emissions across time horizons. Robustness checks employing Driscoll-Kraay Standard Errors, Augmented Mean Group, and Common Correlated Effects Mean Group methods confirmed the consistency of the findings. The study concludes that promoting AI innovation, enhancing financial inclusion, and encouraging renewable energy adoption are essential strategies for reducing CO_2 emissions in the BRICS countries, especially in the context of rising geopolitical uncertainties.

Keywords: Geopolitical Risk; financial Inclusion; AI Innovation; Renewable Energy; BRICS Region

Introduction

The persistent pursuit of fiscal objectives by a nation over a period of time is the fundamental reason behind certain elements that lead to the destruction of ecosystems (Hassan et al., 2024; Hossain et al.,2023). The rise of industry has caused severe ecological degradation, particularly pollution of the environment and air, global warming, the depletion of natural assets, and erosion in biodiversity (Sezgin et al., 2024). Various contaminants, whether occurring naturally or as a consequence of human action, have the potential to exacerbate the atmosphere. Emissions of CO2 are a hazardous pollutant that adversely affects the ecosystem (Sadiq et al., 2024). The world's greatest developing nations BRICS, have seen a huge increase in CO2 production (Mngumi et al., 2024). At a time when researchers are delving deeper into the conflicting balance between economic expansion and the environment, they find themselves at a critical crossroads (Sadik-Zada and Gatto, 2023). According to Tang et al. (2022) and Ming et al. (2022), these countries were liable for 14,759 billion tons of CO2 in 2019. This figure reflects almost 43.19% of the global CO2 emissions generated. Furthermore, making up about 40% of global emissions, the BRICS countries bear a large portion of the blame for the releases of CO2. They are categorized as one of the five carbon-emitting nations due to their significant 41% contribution to worldwide CO2 emissions (Du et al., 2022; Sharif et al., 2020). This demonstrates the vital function they play in combating climate change and transitioning to clean energy sources (Wei et al., 2023; Ridwan,2023). The BRICS group comprises the world's most significant emerging economies, holding for 42% of the worldwide population. UNCTAD (2023) reveal that the BRICS's GDP share of the global economy grew from 18% in 2010 to 26% in 2021. These concerning statistics highlight the importance of ongoing research from the BRICS region's perspective. By considering significant factors such as financial inclusion, AI innovation, and geopolitical risk, we can achieve notable outcomes. Policymakers may implement the findings of the inquiry to promote environmental sustainability in the chosen area. The most important type of green innovation is thought to be sustainable energy technologies and will likely be the primary force behind the development of clean energy sources (Khattak et al., 2024). We must understand the current state of green power investments in the BRICS territory in the context of their historical power policy and economic growth trajectory (Yadav et al.,2024). The BRICS economies' shift towards energy efficiency is indicative of the shifts occurring place in their finances and policies (Azam, 2019). Multiple studies (including Nunez et al., 2023) have underscored the efficacy of employing renewable power resources to lessen the outcome of global warming. Despite exerting significant efforts, these countries have only achieved a capability for environmentally friendly energy that holds about 36% of the global overall. In comparison, the European Union (EU) now possesses 44% of the world's total sustainable power capacity (Wei et al.,2022). The BRICS states have expressed their dedication to participating in worldwide efforts to reduce greenhouse gas emissions within the 2015 Paris Agreement and the hosting of the COP 26 in 2021 (Abbas et al., 2024). Consequently, they are committed to collaborating to accomplish zero emissions by 2050 (Udeagha & Muchapondwa, 2023; Islam et al.,2023).

Our work adds significantly to the current corpus of material. In order to distinguish it from other studies, this research primarily focuses on the frequently ignored field of AI innovation and financial inclusion from the perspective of the BRICS countries. The paper seeks to provide greater details of the correlation between CO2 emissions and AI within the discussed setting, with the goal of assisting in the development of environmentally friendly legislation. Furthermore, it utilizes unique AI data sourced from Our World in Data, specifically focusing on annual AI patent applications. This analysis focuses on trends as well as major study problems within the BRICS zone, namely FNI, GPR, AI, GDP expansion, REN, and CO2 emissions. An important addition to the collection of knowledge is the analysis of CO2 pollution in the BRICS area, which provides researchers with fresh perspectives. This study, being the first to our knowledge to conduct a comprehensive literature analysis, makes us to pursue the following study goals: How do FNI and AI affect the environment in the BRICS countries? What effects do GDP and GPR have on environmental sustainability? This research's importance stems from its attention to the neglected domains of financial inclusion and AI innovation, which have not received much attention from previous studies. To create a sustainable and habitable environment, further research in this area is essential, especially in light of the public's growing interest in green cities and ecological challenges. Using ARDL methodology along with a novel Cobb-Douglas production function, this study looks at how GDP, AI, FNI, REN, and GPR affect carbon emissions from 1990 to 2018. It also uses DKSE, AMG, and CCEMG techniques to ensure the results are robust. Policymakers in the BRICS region and beyond can benefit from the insights this study offer, which will aid in achieving the SDGs and fostering sustainable economic growth.

There are five parts to this paper. The literature review, positioned after this introduction, reviews the relevant work before identifying the research gap. The third section covers the explanations of the analysis variables, methodology, and information sources. The fourth segment covers the outcomes and discussions. The last portion addresses the conclusions and suggestions for policy.

Literature Review

Many economic tools and methodologies have been used in recent studies, combining a variety of different explanatory variables across many geographical locations, and frequently producing contradictory conclusions. Furthermore, little research has been done on the central economic partnerships among the BRICS nations, which could have an impact on the global market. Consequently, in this section, we provide a succinct and critical analysis of the connection between these factors and CO_2 pollutions.

GDP and CO_2 Emission Nexus

Researchers have conducted numerous studies over the years to examine the link between CO_2 emissions and GDP development. More inquiry is required to assess the link between GDP and CO_2 emissions in the BRICS area. Voumik et al. (2023a) adopted the ARDL method to examine the CO_2 emissions of Kenya over the years 1972 to 2021. The outcomes suggest that there prevails an upward connection between a country's emissions level and GDP. Pattak et al. (2023) undertook research in Italy from 1972 to 2021 utilizing the STIRPAT and ARDL methods. They declared that a 1% rise in Italy's GDP in long-term turns 8.08% boost in the release of CO_2. Similarly, multiple investigations, such as He et al. (2019) in China, Finland, and Malaysia, Tufail et al. (2021) in developed nations, Raihan et al. (2023b) in Malaysia, and Ridwan et al. (2023) in France, have identified an encouraging relationship between CO_2 pollutions and GDP. In contrast, Raihan et al. (2024a) undertook an inquiry examining the implication of GDP expansion on CO_2 emissions in India covering 1965 to 2022. Their findings suggested that as the economy grew, there was a slight decline in pollutants. Raihan et al. (2023a) claim that faster GDP growth in China could potentially lead to lower emission levels in the future. In addition, Ridwan et al. (2024a) found that GDP had a major effect on reducing CO_2 emissions, both in the short term and in the long term. Destek et al. (2020) offered decision-makers fresh views on using economic development as a means to enhance the longevity of the environment.

Geopolitical Risk and CO_2 Emission Nexus

Geopolitical risk (GPR) and other social trends among state environmentalists and policymakers have brought up several serious environmental-related challenges (Uddin et al., 2023). Syed et al. (2022) performed an investigation into whether GPR affected the ecosystem in the BRICST countries. Conclusions deployed that CO_2 emissions are falling in the middle and upper quartiles but rising in the lowest quartiles as a result of GPR. Bai (2021) published a study to explore the implications of GPR on the EF in Brazil, Colombia, Mexico, and Russia. They concluded that using GPR reduces carbon footprint. In their study, Adams et al. (2020) assessed the link between GPR and CO_2 emissions in the leading resource-rich nations from 1996 to 2017. Their findings confirm that GPR is associated with a drop in CO_2 emissions. Furthermore, Zhao et al. (2021) found that GPR has an unequal effect on CO_2 emissions, specifically in the BRICS region. Conversely, Cui et al. (2024)

employed sophisticated econometric methods, including CS-ARDL, FMOLS, DOLS, and AMG, to conduct a study in the BRICS nations between 1992 and 2021. Environmental degradation increases in tandem with geopolitical danger, according to the study. Similarly, Li et al. (2024) discovered that, over time, higher emissions of carbon are associated with geopolitical risk in 38 chosen countries. In addition, according to Hunjra et al. (2024), heightened geopolitical danger causes a spike in CO2 emissions and the EF of 21 selected states. In addition, Wang et al. (2022) determined that the govt. of China can successfully consider GPR to control CO2 emissions by boosting environmentally friendly investments and implementing ecological strategies.

Financial Inclusion and CO2 Emission Nexus

Financial inclusion (FNI) is a fundamental element of the economy that is under constant consideration (Sohail et al.,2019). Energy-efficient technologies, enhanced environmental regulations, and readily accessible lending at reduced rates are just a few of the numerous ways in which financial growth exhibit a beneficial influence on our planet (Zaidi et al., 2019; Tanchangya et al.,2024; Ridwan & Hossain, 2024). Raihan et al. (2024c) interpret the effects of financial integration on the release of CO2 in the G-7 zone. According to the ARDL model, the availability of financial resources causes a surge in pollutions level. In addition, Ahmad et al. (2022) deployed the link between FNI and CO2 emissions in BRICS nations and concluded that FNI is a contributing cause for ecological degradation. Hussain et al. (2024) implemented principal component analysis (PCA) to determine that FNI had a detrimental effect on CO2 emissions in the short term but an advantageous impact in the long run in 26 Asian nations. In contrast, Du et al. (2022) utilized several techniques to look at the association between FNI and CO2 emissions. Their study demonstrated that FNI had a destructive association with CO2 emissions, thereby improving the natural well-being of selected developing countries. Renzhi and Baek (2020) determined that FNI is reducing CO2 emissions and made the case that raising environmental consciousness might be an effective way to lessen the adverse impacts of financial growth. According to the AMG's findings, it lowers CO2 emissions, which greatly enhances environmental sustainability. To prevent the adverse impacts of financial openness and to safeguard biodiversity, policymakers should improve the standards of their organizations in the MENA region (Boussaidi and Hakimi, 2024).

AI and CO2 Emission Nexus

To "promote a low-carbon in industry and consistently boost the carbon neutralization of carbon peaks," as well as to help achieve the "double carbon goal," it is imperative that artificial intelligence (AI) be promoted (Xi, 2022; Ridwan et al.,2024e; Rahman et al.,2024). Research on the possible effects of artificial intelligence (AI) on CO2 emissions has begun to emerge as the world undergoes transformation and experiences new kinds of advances in technology. For example, Dong et al. (2024) used dynamic panel data from 30 provinces in mainland China covering the years 2006 to 2019 to build econometric models with the goal of examining the impacts and underlying causes of AI on CO2 emissions. Empirical evidence shows that using AI significantly reduces CO2 emissions. Chen et al. (2022) discovered actual proof indicating that the use of robots greatly decreases CO2 emissions in China's industrial sector. Additionally, Ochieng et al. (2024) have developed an approach that employs robots to monitor and reduce CO2 emissions. Some other authors like Shiam et al.(2024a), Rana et al.(2024), Ferdous et al.(2023), Shiam et al.(2024b), Arif et al.(2024),also concluded similar findings. The system predicts emissions, offers methods for cutting them, and detects pollution using drones and other ecologically conscious sensors. Liu et al. (2023) demonstrated the influence of AI on carbon footprint between 2005 and 2016, leveraging the STIRPAT model. The study's findings reveal that the use of AI significantly mitigates CO_2 releases, as evidenced by several scientific articles regarding AI and robotics in this sector.

Renewable Energy Use and CO2 Emission Nexus

Currently, multiple scholars are investigating the urgent connection between the usage of renewable energy (REN) and the release of CO_2. In order to lower emissions and improve the surroundings, it is crucial to promote alternative power sources for example- sunlight, biogas, geothermal energy, wind energy, and hydroelectric (Jabeen et al., 2020; Atasoy et al.,2022b; Onwe et al.,2024; Raihan et al.,2024e). Ahmad et al. (2024a) made use of the ARDL bound test to assess China's carbon neutrality. They showed that a 1% consumption in REN application should causes to a 0.03% decline in CO_2 pollution over time. Byaro et al. (2023) conducted an evaluation of the association between REN consumption and environmental harm in 48 sub-Saharan African states. For their analysis, they used categorized panel quantile regression. Research has demonstrated that using renewable energies reduces environmental harm on several levels. Additionally, Rahman and Alam (2022) look to see if using renewable energy can lower Bangladesh's CO_2 emissions. The study used the PMG and NARDL approaches, and its conclusions illustrate that harnessing sustainable power helps Bangladesh reduce its CO_2 emissions. Similarly, Raihan et al. (2022a) in China, Isik et al. (2024) in 27 OECD countries, and Kwilinski et al. (2024) in the EU transportation sector expressed the same conclusion. However, Rehman et al. (2023) researched the worldwide influence of nuclear power and REN on CO_2 emissions from 1985 to 2020. The outcomes demonstrate that the adoption of REN does not have the ability to alter the levels of CO_2 emissions either in the long run or in the short run. Shang et al. (2024) found a U-shaped link between environment friendly energy and pollutions when examining China's REN and CO_2 pollutions from 1995 to 2020.

Literature Gap

The work observes that no prior research has looked at the BRICS countries in extensive detail. However, a limited number of studies have explored the connection among GDP expansion, the utilization of green power, and CO_2 emissions. By adding new distinct variables, such as financial inclusion, geopolitical risk, and AI innovation, this analysis adds to the body of expertise. We found that the majority of earlier studies had difficulty drawing meaningful results. Furthermore, there is a dearth of research on environmental damage, especially concerning the sophisticated variables of AI innovation and financial inclusion, which have the potential to foster green development and reduce carbon pollution. As a result, this study examines the most recent data for the BRICS states, providing a longer time frame and comprehensive insights into past carbon emissions patterns among the countries. By concentrating on these important factors, this study ultimately seeks to improve understanding of how the BRICS nations contribute to their economic success and ecosystem health.

Methodology

Data and Variables

The inquiry used sophisticated statistical approaches to understand the complex correlation between the selected factors. The study's dependent variable, CO_2, came from the reliable WDI. The WDI (2022) also provided data for GDP and renewable energy utilization, while reputable sources such as Our World in Data, the GPR Index, and Global Financial Development provided information on AI innovation, geopolitical risk, and financial inclusion. Table 1 provides a thorough summary of all the variables examined, along with definitions, sources, and units of measurement.

Table 1. Variable and sources of data

Variables	Description	Logarithmic Form	Unit of Measurement	Source
CO_2	CO_2 Emission	LCO_2	CO_2 Emission (kt)	WDI
GDP	Gross Domestic Product	LGDP	GDP per capita (current US$)	WDI
GPR	Geopolitical Risk	LGPR	Geopolitical Risk Index	GPR Index
FNI	Financial Inclusion	LFNI	Automated teller machines (ATMs) (per 100,000 adults)	Global Financial Development
AI	AI Innovation	LAI	Annual patent applications related to AI	Our World in Data
REN	Renewable Energy Use	LREN	Renewable Energy Consumption (% of total final energy consumption)	WDI

Theoretical Framework

Cobb and Douglas (1928) statistically examined the Cobb-Douglas production function, commonly adopted to illustrate the association concerning input and output components. The primary goal is to conduct a deeper analysis of the complicated relationship between the utilization of clean energy, GDP growth, financial inclusion, geopolitical risk, and AI advancements, and their impact on CO2 pollutions in BRICS area. Equation (1) depicts the structure of the Cobb-Douglas production function.

$Y_t = f(K_t, L_t)$ …………………………………..(1)

Here, Y_t indicates the GDP at time t. On the other hand, K_t represents capital at t time and L_t means effective labor at t time. Nowadays, ecological economics makes use of this function (Nicolle et al.,2023). Economic progress has been linked to CO2 emissions in the past (Mensah et al. 2019; Aye and Edoja, 2017). From here on out, the creation function can look like this:

$CO_{2t} = f(GDP_t)$ …………………………………..(2)

Disruptions in energy supply due to global conflicts can push nations to depend more on carbon-intensive energy sources. Additionally, increasing access to finance can drive modernization and GDP growth in emerging nations, both of which can lead to higher carbon emissions. Now, the function can be present like-

$CO_{2t} = f(GDP_t; GPR_t; FNI_t)$ …………………………………..(3)

In contrast, although growing use of green power promptly reduces the release of CO2 by substituting fossil fuels with alternative sources such as wind and solar energy, AI has a varied impact on pollution levels.

$CO_{2t} = f(GDP_t; GPR_t; FNI_t; AI_t; REN_t)$ …………………………………..(4)

The equation (5) represents the economic model and is clarified as the actual context in the next way:

$CO_{2t} = Z_0 + \partial_1 GDP_t + \partial_2 GPR_t + \partial_3 FNI_t + \partial_4 AI_t + \partial_5 REN_t + \mu_t$ …………………………………..(5)

In this case , $\partial_1, \partial_2, \partial_3, \partial_4, \partial_5$, ∂_6used as the coefficients whereas, Z_0 and μ_t illustrate the intercept and error terms. Moreover, the logarithmic version of equation (5) can be presented like:

L$CO_{2t} = Z_0 + \partial_1 LGDP_t + \partial_2 LGPR_t + \partial_3 LFNI_t + \partial_4 LAI_t + \partial_5 LREN_t + \mu_t$
…………………………………..(6)

Because the coefficient indicates the elasticity, this formulation is more beneficial and eliminates the problem of multicollinearity (Akther et al.,2024; Sohail et al.,2018b).

Empirical Methodology

The cross-sectional hyperlink and panel data features point to a chance that the BRICS countries are dealing with a stationary mixed-order problem. Therefore, we employ the slope homogeneity test and CSD. In this endeavor, we need to validate the CSD and SH issues through cointegration analysis and first and second-generation panel unit root tests. We carefully considered each of these factors and selected the ARDL method. The research analyzed the estimations of DKSE, AMG, and CCEMG to assess robustness. This part provides a clear and brief description of the research findings, their interpretation, and any possible repercussions for the study.

Cross Sectional Dependence Test

If researchers ignore this issue and handle the cross-sections as isolated, CSD can result in distorted, deceptive, and contradicting results (Hoyos et al., 2006). The optimum test to utilize is the CSD test, even if a standard unit roots testing shows cross-sectional independence (Sahoo & Sethi, 2021). In order to investigate CSD, this study uses Pesaran's (2015) technique with full panel data and weakly exogenous components.

$$CSD = \sqrt{\frac{2T}{N(N-1)N}\left(\sum_{i=1}^{N-1}\sum_{m=i+1}^{N}\widehat{Corr_{\iota,t}}\right)} \text{……………………… (7)}$$

Slope Homogeneity Test

Slope heterogeneity (SH) must be considered when evaluating panel data (Voumik and Mimi, 2023; Mithun et al.,2023). Because cross-sections usually show similar features, panel data typically have consistent slopes so addressing slope uniformity is essential (Ayad and Djedaiet, 2022). Following that, we apply in our work the SH test developed by Pesaran and Yamagata (2008). The SH is shown by Equation (8) as follows:

1. $\breve{\Delta} = \sqrt{N}\left(\frac{N^{-1}S\%-k}{\sqrt{2k}}\right)$ and $\breve{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}S\%-k}{\sqrt{\frac{2k(T-k-1)}{T+1}}}\right)$…………………. (8)

Panel Unit Root Test

According to the scientific community, it is widely accepted that identifying the integration order of the series is a vital prerequisite for exploring any connections between variables (Voumik et al., 2023b; Ahmad et al.,2024b). Im et al. (2003) developed the initial IPS test, while Pesaran (2007) created the subsequent version of the CIPS test and the CADF unit root examinations. The IPS test can be represented in the following way:

$$\Delta y_{it} = \alpha_i + \beta_i t + \gamma y_{it-1} + \delta_i \Delta y_{it-1} + \varepsilon_{it} \ldots\ldots\ldots\ldots (9)$$

The first generation of panel unit root testing overlooks heterogeneity, CSD implications, and over-rejection of null hypotheses (Choi, 2001). The purpose of the CIPS analysis is to take into consideration the possibility of CSD in the panel data, which, if left unchecked, could result in inaccurate inference (Polcyn et al.,2023). The CIPS test is conducted using Equation (10):

$$CIPS = \frac{1}{N}\sum_{t=1}^{N} t_1(N,T) \ldots\ldots\ldots\ldots (10)$$

The CADF test has a strong relationship with the CIPS test and the equation is given below:

$$\Delta Yi_t = \varphi_i + \rho i Yi_{t-1} + \varphi i \bar{Y}_{t-1} + \sum_{j=1}^{m} \varphi_{ij} \bar{Y}_{t-1} + \sum_{j=1}^{m} \gamma_{ij}\, \Delta Y_{i,t-1} + \varepsilon_{it} \ldots\ldots\ldots (11)$$

Panel Cointegration Test

The authors administer the cointegration test after completing the unit root assessments. In this investigation, we applied the second-generation panel cointegration approach to determine the cointegration relationships between the relevant variables (Westerlund, 2007). We generate statistics from the four-panel cointegration test.

$$G_a = \frac{1}{n}\sum_{i=1}^{N} \frac{\acute{a}_\iota}{SE(\acute{a}_\iota)} \ldots\ldots\ldots\ldots (12)$$

$$G_t = \frac{1}{n}\sum_{i=1}^{N} \frac{T\acute{a}_\iota}{a_\iota(1)} \ldots\ldots\ldots\ldots (13)$$

$$P_t = \frac{\acute{a}}{SE(\acute{a})} \ldots\ldots\ldots\ldots (14)$$

$$P_a = T\acute{a} \ldots\ldots\ldots\ldots (15)$$

In this case, mean group statistics are represented by Gt and Ga, and cointegration is symbolized by Pt and Pa.

Panel ARDL Framework

Pesaran et al. (2001) proposed the panel autoregressive distributed lag (ARDL) technique, which was adopted in this study due to its ability to handle variables that are either I(0), I(1), or a combination of both (Raihan et al., 2024e; Sohail et al., 2018a). The ARDL model is advantageous over models like OLS, VECM, and VAR because of its flexibility in defining lag lengths and its effectiveness in both short- and long-term estimations (Voumik and Ridwan, 2023). Although it operates differently from traditional cointegration methods, the ARDL model offers several advantages, such as its ability to address endogeneity by incorporating variable lag periods (Pesaran et al., 2001; Abir, 2024). A key strength of the model is its robustness in estimating systems with mixed levels of integration (Ullah et al., 2021; Ridzuan et al., 2023; Raihan et al., 2024f), enabling it to account for the integration properties of variables. This feature enhances the model's ability to reflect real-world dynamics and effectively capture complex temporal relationships, as noted by Raihan et al. (2024b).

$$\Delta LCO_{2it} = \beta_{1i} + \gamma_{1i} LCO_{2i,t-1} + \gamma_{2i} LGDP_{i,t-1} + \gamma_{3i} LGPR_{i,t-1} + \gamma_{4i} LFNI_{i,t-1} + \gamma_{5i} LAI_{i,t-1} + \gamma_{6i} LREN_{i,t-1} + + \sum_{j=1}^{p} \lambda_{1i} \Delta LCO2_{i,t-j} + \sum_{i=0}^{q} \lambda_{2i} \Delta LGDP_{i,t-j} + \sum_{i=0}^{q} \lambda_{3i} \Delta LGPR_{i,t-j} + \sum_{i=0}^{q} \lambda_{4i} \Delta LFNI_{i,t-j} + \sum_{i=0}^{q} \lambda_{5i} \Delta LAI_{i,t-j} + \sum_{i=0}^{q} \lambda_{6i} \Delta LREN_{i,t-j} + \varepsilon_{1i,t} \quad (16)$$

Furthermore, this paradigm is useful in any situation where investigative series integration is involved (Voumik et al., 2023c). When series variables are cointegrated, we can evaluate the short-run effects of GDP, AI innovation, GPR, FNI, and REN on CO2 emissions using an error-correcting mechanism (ECM). The ECM, defined as Eq. (17), used for long-term link between each factor.

$$\Delta LCO2_{it} = \sum_{j=1}^{p-1} \alpha_{1ij} \Delta LCO2_{i,t-j} + \sum_{i=0}^{q-1} \alpha_{2ij} \Delta LGDP_{i,t-j} + \sum_{i=0}^{q-1} \alpha_{3i} j \Delta LGPR_{i,t-j} + \sum_{i=0}^{q-1} \alpha_{4i} j \Delta LFNI_{i,t-j} + \sum_{i=0}^{q-1} \alpha_{5ij} \Delta LAI_{i,t-j} + \sum_{i=0}^{q-1} \alpha_{6ij} \Delta LREN_{i,t-j} + \mu_{1i} ECT_{1,it-1} + \varepsilon_{1i,t} \quad (17)$$

Robustness Check

We found out how stable the model was by comparing the effects of time-dependent parts on the environment using the DKSE created by Driscoll and Kraay (1998), the AMG (Bond & Eberhardt ,2009), and the CCEMG created by Pesaran (2006) in our study. We use DKSE in CSD problems because it is heteroscedastic, autocorrelation-consistent, and resistant to typical forms of CSD (Hoechle, 2007). Due to their consideration of the correlation among panel members, the AMG and CCEMG estimators are both resistant to CSD (Ng et al., 2020). Furthermore, according to Kapetianos et al. (2011), the CCEMG approach is resilient to structural fractures and non-stationary prevalent elements that go unnoticed.

Results and Discussion

Based on a dataset encompassing the BRICS countries from 1996 to 2019, Table 1 showcases the statistical findings for several normality metrics, such as skewness, probability, kurtosis, and the Jarque-Bera test. Each variable has 100 observations. Highlighted are the descriptive statistics for the following seven variables: LCO2, LGDP, LGPR, LFNI, LAI, and LREN. The table indicates that all variables have positive means, except LGPR. In addition, almost all of the parameters have relatively low standard deviations, suggesting that the data points are somewhat shifting over time and clustered around the mean. Most variables show positive skewness, except for LCO2, which is positively skewed. Furthermore, the Jarque-Bera test was utilized to verify the level of normality of each factor in this investigation. This type of test is suitable as it takes into account inconsistencies related to both skewness and kurtosis.

Table 2. Summary statistics of variables

Statistic	LCO2	LGDP	LGPR	LFNI	LAI	LREN
Mean	14.01781	8.744605	-1.829589	3.868414	3.054113	2.772809
Median	14.25714	8.808211	-1.534152	4.028851	3.113269	2.685356
Maximum	16.19161	9.22577	0.14121	5.222552	3.89182	3.890186
Minimum	12.55836	7.693433	-3.912023	2.581988	1.791759	1.156881
Std. Dev.	1.114343	0.391927	1.202445	0.800042	0.500842	0.952693
Skewness	0.475347	-1.100278	-0.176032	-0.011587	-0.405564	-0.454151
Kurtosis	2.113849	3.526287	1.548373	1.502311	2.437028	1.90319
Jarque-Bera	7.037847	21.33094	9.296546	9.348368	4.061935	8.450011
Probability	0.029631	0.000023	0.009578	0.009333	0.131209	0.014625
Sum	1401.781	874.4605	-182.9589	386.8414	305.4113	277.2809
Sum Sq. Dev.	122.9343	15.20711	143.1416	63.36673	24.83345	89.85468
Observations	100	100	100	100	100	100

Cross Sectional Dependence test

In Table 3, at the 1% level, all CSD statistic values are highly significant, and the p-value for each variable is less than 0.05. These findings reject the null hypothesis, which asserts no cross-sectional dependence between nations, for all factors. It indicates that an unforeseen incident in one of the chosen countries might have consequences for the other nations as well.

Table 3. Results of CSD test

Variables	CD-Statistics	P-Value
LCO_2	10.13***	0.000
LGDP	13.26***	0.000
LGPR	7.68***	0.000
LFNI	11.62***	0.000
LAI	2.15**	0.025
LREN	4.17***	0.000

Table 4 summarizes the outcomes of the slope heterogeneity experiment. The calculated p-values of 0.000 reject the null hypothesis, stating that the slope coefficients are homogeneous, at the 1% significance level. The p-values reject the homogeneity hypothesis, demonstrating that multiple variables have distinct coefficients.

Table 4. Results of Slope Homogeneity test

SH tests	Δ statistic	P-value
$\breve{\Delta}$ test	4.065***	0.000
$\breve{\Delta}_{adj}$ test	5.062***	0.000

Note: "Null Hypothesis: Slope of the coefficients are homogenous"

Table 05 provides the unit root analysis conclusions. At the 1% significance threshold, the IPS test confirms that only LGPR and LAI are stationary at the level form I(0), whereas the other variables appear to exhibit significant and stationary patterns at the first difference I(1). The results of the CIPS test demonstrate that LAI is stationary at the 1% level and LGPR is stationary at the I(0) level at the 5% significance threshold. At the 1% significance level, the remaining factors are stationary at the initial difference, I(1). Similar to this, the CADF unit root examination finds that, at the 1% significance level, only LGPR and LAI are stationary at the level form I(0), but all the others start to become stationary at the first difference I(1). Furthermore, following the first difference, everything else is significant in the 1% range. Our results rule out the notion of a unit root problem by indicating that the variables reflect strong cointegration.

Table 5. Results of panel Unit root test

Variables	IPS		CIPS		CADF		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LCO2	-1.554	-3.950***	-2.183	-2.842***	-1.029	-3.053***	I(1)
LGDP	-0.018	-3.041***	-2.045	-3.651***	-0.764	-3.201***	I(1)
LGPR	-4.098***	-6.383***	-2.524**	-5.296***	-3.021***	-5.064***	I(0)
LFNI	-0.121	-3.132***	-2.225	-3.707***	-1.552	-3.881***	I(1)
LAI	-3.933***	-7.003***	-3.071***	-5.323***	-2.980***	-3.871***	I(0)
LREN	-1.535	-4.031***	-1.750	-3.226***	-0.780	-4.586***	I(1)

The Westerlund (2007) cointegration assessment evaluates long-term relationships between variables in Table 06 using four test statistics (Gt, Ga, Pt, and Pa). P-values less than 0.05 for the Gt and Pt test statistics partially confirm the null hypothesis, suggesting cointegration and a consistent, persistent connection between the variables in the panel dataset.

Table 6. Results of panel Cointegration test

Statistics	G_t	G_a	P_t	P_a
Value	-3.761***	-6.570**	-4.904**	-3.877***
Z-Value	-1.872	1.901	2.087	1.704
P-Value	0.001	0.017	0.043	0.001

The Panel ARDL model's results, presented in Table 07, demonstrate the intricate dynamics influencing the BRICS region's carbon pollution. In terms of LGDP, the short-term coefficient is 0.3017 while the long-run coefficient is -0.4131, and both are statistically significant at conventional levels. This suggests that economic expansion alone contributes to environmental degradation in this setting. Our implications are agreed by Addai et al. (2023) in Eastern Europe, Syed et al. (2022) in BRICST, Ridwan et al.(2024d) within USA, Gessesse and He (2020) in China, Rahman et al.(2022) in Bangladesh, Raihan et al.(2024h) within Bangladesh, Raihan et al.(2024d) in Indonesia and Kongkuah (2021) in OECD economies. Furthermore, Minh et al. (2023) demonstrate a link within GDP development and CO2 emissions, which declines in Vietnam beyond a specific threshold. Similarly, LGPR has a positive association with LCO2 in both periods. In the short run, the coefficient has a positive value of 0.0206, and in the long run, the value is 0.1362. The variable is significant because its p value is less than the conventional level for both periods. Our results align with Dun and Wang (2023) in China, Adedoyin et al. (2020) in EU countries, and Gyamfi et al. (2021) in E-7 zones. In contrast, in the short and long terms, there is a negative link between LFNI and LCO2. The short-term is insignificant as the p value is 0.0993, and the long-term results are significant as the p value is 0.0006. These findings demonstrate that financial accessibility has a positive effect on the BRICS ecosystem. For every 1% increase in LFNI, LCO2 reduces by 0.0472% in the near term and 0.1061% in the long term. Usman et al. (2021) found support for this conclusion in the 15 highest emitting countries, Saqib et al. (2023) in emerging economies, Raihan et al.(2022b) within USA and Tamazian and Rao (2010) in transitional countries. But Musah (2021) found that financial inclusion causes more carbon emissions in Ghana.

Similarly, there is an obvious connection between AI innovation and the environment, as evidenced by the beneficial relationship observed between LCO2 and LAI across both short and long periods. Specifically, a 1% expansion of LAI will cut LCO2 by 0.0094% in the short term and by 0.1221% in the long term. These results imply that utilization of modern AI technology could boost ecological conditions in both terms, and the results are significant in long terms and insignificant in short terms. This result is supported by Ridwan et al.(2024b) in USA, Ridwan et al.(2024c) in G-7 countries Akther et al.(2024) in USA, Bala et al. (2024) in G-7 countries, Abir et al.(2024) in USA, Shiam et al.(2024c) in Nordic area and Hossain et al.(2024) within Nordic region. Mor et al. (2021) studied in the Indian agricultural sector is consistent with these findings. Chen et al. (2022) discovered that the use of industrial robots in a variety of industries can minimize the ecological impact, particularly across 72 nations. By using artificial intelligence (AI), humans can better manage climate change and achieve sustainability while using natural assets (Habila et al., 2023; Faruk et al.,2023). In both the short and long term, the table demonstrates an inverse relationship between LREN and LCO2.

Table 7. Results of Panel ARDL test

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
Long-run Estimation				
LGDP	0.4131	0.0734	5.6323	0.0000
LGPR	0.1362	0.0581	2.3438	0.0227
LFNI	-0.1061	0.0291	-3.6655	0.0006
LAI	-0.1221	0.0445	-2.7411	0.0082
LREN	-0.8690	0.1056	-8.2326	0.0000
Short-run Estimation				
COINTEQ01	-0.1535	0.0807	-2.9021	0.0624
D(LCO2(-1))	-0.0050	0.0670	-1.0751	0.0404
D(LGDP)	0.3017	0.1345	2.2433	0.0289
D(LGPR)	0.0206	0.0082	2.5010	0.0154
D(LFNI))	-0.0472	0.0894	-1.5284	0.0993
D(LAI)	-0.0094	0.0054	-1.7437	0.0868
D(LREN)	-0.5075	0.3068	-3.6540	0.0038
C				

The long-term and short-term results reveal statistical significance, as the p value is less than the conventional thresholds. Over time, there will be a 0.8690% reduction in LCO2, and in a short time, there will be a reduction of 0.5075% for every 1% increase in LREN. In particular, the effect indicates that consumption of green energy reduces emissions. The findings of Aziz et al. (2021) for MINT countries, Raihan et al.,(2024f), Islam et al.(2024) in top nuclear energy consuming area, Atasoy et al.(2022a) within USA, Raihan et al. (2024g), Mahmood et al. (2019) for Pakistan, and Attiaoui et al. (2017) for Africa align with our findings.

Table 8 uses three different estimate approaches (DKSE, AMG, and CCEMG) to establish the consistency of the ARDL results. For each method, the estimated LGDP coefficients are 0.472, 0.456, and 0.174, respectively, and all estimators' exhibit significance at the 1% level. These findings are consistent with the short- and long-term outcomes of the ARDL paradigm, indicating that economic growth has had a detrimental influence on natural health in the BRICS countries. In a similar vein, the LGPR coefficient indicates negative correlations in the AMG approach but positive correlations in the DKSE and CCEMG calculations. In particular, LCO2 increases by 0.820% in DKSE and 0.034% in CCEMG for each percent rise in risk related to geopolitics, but AMG forecasts a 0.923% drop in carbon emissions.

Table 8. Results of Robustness check

VARIABLES	(1) DKSE	(2) AMG	(3) CCEMG
LGDP	0.174***	0.456***	0.472***
	(0.263)	(0.099)	(0.158)
LGPR	0.820***	-0.923***	0.034**
	(0.038)	(0.013)	(0.059)
LFNI	-0.108***	-0.116***	-0.178**
	(0.107)	(0.038)	(0.094)
LAI	-0.116***	-0.034**	-0.027**
	(0.156)	(0.078)	(0.047)
LREN	-0.196**	-0.469***	-0.292
	(0.085)	(0.090)	(0.213)
Constant	14.22***	11.79***	9.670***
	(2.632)	(1.325)	(2.021)
Observations	100	100	100
Number of groups	5	5	5
R-squared	0.971	0.988	0.864

Note: Standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$

In DKSE, AMG, and CCEMG, the LGPR factor is statistically significant at the 1% and 5% thresholds, accordingly. On the other hand, the opposite relationship between LFNI and LCO2 suggests that ongoing financial inclusion has no adverse effects on the BRICS atmosphere. In the CCEMG estimation, the LFNI coefficient is significant at the level of 5%, but in other approaches, it is significant at the 1% threshold. All three investigations have found a negative correlation between LCO2 and LAI. In the AMG and CCEMG analyses, the LAI coefficient is significant at the 5% level; in the DKSE test, it is significant at the 1% range. According to such outcomes, a 1% increase in AI innovation cuts LCO2 by 0.116%, 0.034%, and 0.027%, respectively, implying that higher AI innovation contributes to the BRICS ecosystems. Similarly, favorable interactions between LCO2 and LREN illustrate that greater utilization of clean energy has an excellent consequence for biodiversity in the regions under investigation. In the CCEMG estimation, the LREN variable is not significant, but it is significant at the 1% level in AMG and the 5% level in DKSE. These findings verify the implications of the experiment and reinforce the ARDL model, which was the main estimating approach deployed.

Conclusion and Policy Recommendation

This investigation looked at the complex relationship among CO2 emissions, renewable energy use, geopolitical risk, financial inclusion, AI innovation, and GDP expansion in the BRICS nations between 1996 and 2022. The research sought to determine the key factors changing environmental conditions in this region by utilizing the Cobb-Douglas production function and advanced econometric methodologies. To make sure that there are no unit root problems in the dataset and to tackle all possible empirical difficulties, our study performed both first-generation and second-generation panel unit root examinations. Panel cointegration tests further highlighted the variables' dependency and validated their long-term cointegration. This investigation also utilized the ARDL framework to capture the short- and long-term connection between the selected variables. We fully investigated the correlations between dependent and independent variables using the DKSE, AMG, and CCEMG techniques to validate strong conclusions. The results revealed that while economic expansion and geopolitical risk raise CO2 emissions, financial inclusion, AI innovation, and the use of clean energy had a beneficial effect on the environmental sustainability of the BRICS blocks. Through the use of modern technology and inclusive growth in finances, this evaluation underscored the importance of the diverse elements influencing environmental sustainability in the BRICS region. In order to ensure ecological viability, the paper advocates the adoption of fresh political approaches that support sustainable growth in GDP and AI technology adoption. In the end, this research provides a basis for informed decisions aimed at improving environmental preservation and the implementation of green energy techniques, thereby increasing resilience and prosperity in this region.

This study’s findings highlight several policy suggestions for the BRICS countries as they navigate the complicated link between economic growth, geopolitical risks, and environmental sustainability. It is important to recognize the strong association between GDP and CO2 emissions, which highlights the necessity for implementing policies that separate economic growth from carbon emissions. This could include encouraging the adoption of green technologies, enhancing energy efficiency, and advocating for environmental friendly industrial practices. Given the negative effects of geopolitical risks on CO2 emissions, it is critical for BRICS policymakers to prioritize diplomatic engagement and conflict resolution in order to promote geopolitical stability. Additionally, they should focus on implementing domestic policies that address the environmental consequences of these risks. In addition, the research deploys the requirement of AI innovation in addressing carbon emissions. It recommends that BRICS governments focus on investing in AI-driven solutions to optimize energy usage and minimize environmental impact in different industries. Moreover, the significant influence of accessibility in finances on decreasing CO2 pollutions indicates that by increasing access to financial services, more individuals can engage in environmentally conscious investments and embrace sustainable behaviors. This is especially crucial for marginalized communities. Policies that promote financial literacy, microfinance, and digital banking can have a significant impact on fostering an inclusive green economy. The significant decrease in CO2 emissions linked to the use of renewable energy emphasizes the urgency for BRICS nations to foster their shift to sustainable energy resources. This may include the consideration of enhanced subsidies for renewable energy projects, the implementation of more stringent regulations on fossil fuel consumption, and the allocation of resources towards the development of infrastructure that facilitates the seamless integration of renewable energy into national grids. Furthermore, the validation of these findings using rigorous econometric techniques indicates that these policy measures are not only effective, but also able to withstand various economic conditions and political landscapes. By embracing a comprehensive approach that incorporates these valuable insights, BRICS countries have the potential to successfully tackle the intertwined issues of maintaining economic growth and mitigating climate change. This can be used as a model for other nations to emulate on a global scale. It is crucial for BRICS policymakers to work together, think creatively, and put these strategies into action to secure a stable and strong future for their economies and the global environment.

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