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Does green innovation reduce environmental degradation? A panel threshold analysis for BRICS countries

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ABSTRACT

In this present age, innovation has become inextricably tied to both long-term economic growth and environmentally sound development. In this context, the impact that environmentally focused technological advancements or innovations have on environmental quality is of the utmost importance. Therefore, the main goal of the present study is to determine how Green innovation (*GI*) affects environmental degradation in the BRICS countries from 1992 to 2021. The ecological footprint (*EFT*) is an indicator used in the study to measure environmental degradation. The study divides the components that contribute to the explanation into two categories: the *GI* threshold variable and the independent variables *RE*, *GDP*, and population (*POP*). Additionally, this study investigates the indirect impact of *RE*, *GDP*, and *POP* through the threshold effect of *GI*. The stochastic impacts of the explanatory factors are explored using sophisticated panel data estimation methods and a panel threshold model. According to the findings of the study, an improvement in environmental quality occurs when the threshold level of *GI* is achieved, which indicates that innovation in the form of a lower *EFT* is responsible for the improvement. In light of the findings, recommendations for policymakers and stakeholders in BRICS countries are to promote *RE* and drive *GI*.

1. Introduction

Preventing environmental degradation and guaranteeing sustainable development are now global challenges [1]. The ecological footprint (*EFT*) is a recently introduced measure of environmental degradation that considers all environmental information of a country. Moreover, it also assesses both biological potential and demand for natural resources [2]. A wide range of topics related to *EFT* and pollution, such as economic complexity, energy consumption, globalization, renewable energy (*RE*), international trade, etc., have been researched [3–7]. These studies found that the majority of developing countries began the process of industrialization in order to promote economic development against the backdrop of a world that is becoming increasingly interconnected. As a consequence, energy consumption and trade opportunities rise, necessitating the production of more items. Through production and consumption, energy usage in this process has a significant influence on *EFT* [8].

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Recently, rapid economic growth has raised concerns about resource scarcity and environmental sustainability around the world. According to Ref. [9], BRICS[1] are responsible for more than 25 % of the world's carbon dioxide (CO2) emissions. More specifically, they are not immune to ecological issues and environmental degradation due to their rapid rise in growth over the previous two decades [10]. For instance, population growth in China and India is associated with rising energy consumption and greater resource exploitation, both of which worsen the environment. This suggests that BRICS have a significant role in global emissions due to increasing resource exploitation and energy usage [11–14]. Therefore, these economies have a mounting need to develop and put into practice environmental policies that would help reduce their ecological and carbon footprints.

The BRICS countries, which together make up 41 % of the world's population, 21 % of its GDP, and $4 trillion in foreign exchange reserves, have significantly influenced the global economy [15]. Since increasing industrialization and resource exploitation are both consequences of growing economic expansion, the BRICS countries are thus a significant source of global CO2 emissions. Additionally, the exploitation of natural resources has led to a rise in environmental pollution as a result of the depletion of biocapacity [16]. Because in these countries, traditional energy sources like coal, oil, and gas, as well as the import of comparable energy factors, are primarily used in the production process. Hence, it is imperative to prevent the misuse of these resources, especially in the form of environmental degradation. Fig. 1 illustrates how the BRICS have seen a persistent trend toward *EFT* during the last 20 years, especially in China, India, and Russia.

BRICS countries are recognized as rising economic powers and are projected to become among the four most dominant economies by 2050. To be more precise, the BRICS countries had about 40 % of the world's population in 2021 and contributed nearly 30 % of the world's GDP.[2] In addition to this, the BRICS countries have a wealth of energy resources, and their growth trajectory, which is heavily reliant on the energy use has captured the attention all over the globe [17]. But the BRICS countries are now dealing with the challenge of increasing *EFT* levels while simultaneously experiencing a decline in their ecological capacity [18]. They are without a doubt the most important aspect of innovation because of the enormous economic growth potential that they possess. In this regard, green innovation (*GI*) can provide clean environment by lowering environmental degradation. In terms of renewable energy (*RE*), BRICS economies have started increasing share of *RE* sources in their total energy mix. According to Institute for Energy Economics and Financial Analysis (IEEFA)[3] (2016), BRICS countries have jointly invested 130US$ in development of *RE*. All of these circumstances point to the fact that it is essential to give the BRICS countries a greater amount of attention. As a consequence, the main goal of this research is to assess how *GI* and *RE* affect *EFT* in the BRICS countries. This is an important step towards improving the state of the ecological environment and addressing other issues pertaining to the environment.

This research holds significant importance, distinguishing itself from existing studies by examining the potential reduction in environmental degradation through the lens of green innovation. Drawing upon the most up-to-date ecological footprint data, this study builds upon prior research on sustainable development within the BRICS countries, offering a fresh perspective on how to enhance the environmental quality of these emerging economies. Furthermore, this research employs advanced panel data estimation techniques to delve into the intricate relationships between the variables under scrutiny. The investigation utilizes the cointegration test proposed by Ref. [19] and the Augmented Mean Group (AMG) model, considering the inherent cross-sectional dependence (CD) within the panel data. Additionally, this study delves into the transmission relationships and underlying mechanisms among green innovation, renewable energy, economic growth, population, and environmental degradation across BRICS countries. These novel insights have the potential to guide BRICS countries in preserving environmental quality and can offer valuable policy recommendations to traverse similar development trajectories.

The further sections of the research are outlined as follows: In Section 2, the literature review is presented. Section 3 of the study contains theoretical framework and hypothesis of the study. The data and methods used in the study are described in Section 4. Section 5 provides an explanation of the empirical findings. The study is concluded in Section 6.

2. Literature review

Over the course of more than two centuries, the field of economics has undergone significant transformation, evolving into the academic discipline of sustainable development. In recent decades, the non-renewability of natural resources has posed a substantial challenge to long-term global economic development, with environmental instability and pollution emerging as pressing concerns. In this regard, environmental policies aimed at reducing negative ecological impacts have gained significance worldwide. Green innovation (*GI*) and sustainable goods production have emerged as pivotal strategies to simultaneously curtail environmental harm and yield financial and societal benefits by reducing operational costs [20]. Investigating the period from 1991 to 2018 [15], conducted an insightful analysis of *GI* and renewable energy (*RE*) effects on carbon emissions across the top 10 polluting countries. Their research, employing the Moment Quantile Regression (MMQR) method, revealed that *GI* exerted a more substantial influence in reducing emissions within the highest emissions quantiles, while its impact was comparatively muted in the lowest quantiles. In a complementary study [21], observed the positive impact of *GI* on the environmental sustainability of BRICS countries from 1990 to 2014 [22]. further contributed to this discourse by utilizing the Pooled Mean Group (PMG) estimation method, suggesting the potential long-term benefits of *GI* for environmental sustainability [23]. explored the connection between ecological footprint (*EFT*) and *GI* for the top 20 countries from 1993 to 2016. The findings shed light on how economic development is primarily responsible for environmental

[1] Brazil, Russia, India, China, and South Africa.
[2] The World Bank (2023).
[3] https://ieefa.org/.

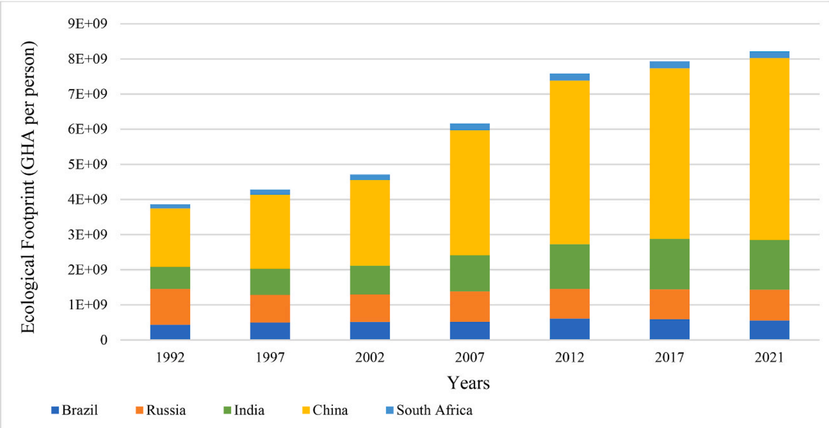

Fig. 1. Ecological footprint in BRICS countries (1992–2021).

degradation, while investments in *GI* can facilitate sustainable development.

The relationship between *GI* and environmental quality has attracted considerable empirical scrutiny. For instance Ref. [24], found that in OECD countries, *GI* effectively reduces CO2 emissions. Similarly [25], analyzing a panel dataset for G7 countries, uncovered a dynamic relationship between *EFT* and *GI*, establishing the utility of *GI* in mitigating environmental challenges [26]. extended this inquiry by examining the impact of *GI* on *EFT* in the BRICS economies from 1992 to 2016, demonstrating how environmental advancements can forestall degradation [27]. explored the relationship between *GI* and environmental quality in OECD member countries. The study affirms *GI's* role in enhancing environmental sustainability and corroborates findings observed in other studies [28–30].

Concurrently, numerous studies have scrutinized the nexus between environmental quality and *RE* [31]. highlighted that *RE* effectively reduces CO2 emissions, particularly in high- and middle-income countries. [32], employing the ARDL technique, demonstrated that *RE* deployment reduced CO2 emissions intensity in 25 major emerging economies from 1990 to 2018. Conversely [21], identified a detrimental impact of *RE* on CO2 emissions in China from 1990 to 2019. Additionally [33], offered empirical evidence indicating that *RE* enhances environmental quality in 16 EU member states [34]. emphasized that *RE* fosters environmental sustainability across 20 developing countries, while non-renewable energy exacerbates ecological degradation. These findings are in alignment with [35], who demonstrated a lower environmental impact of *RE* using data from developing countries spanning from 1990 to 2016.

In summary, extant literature has presented varying conclusions regarding the relationship between green innovation, renewable energy consumption, and environmental degradation, often stemming from differences in data, methodologies, and study periods. Moreover, studies examining ecological footprints have typically relied on data only up until 2017. Therefore, this research endeavors to provide a fresh perspective by evaluating the influence of green innovation on environmental degradation. Notably, this study stands out as the first to utilize ecological footprint as a surrogate variable within the latest dataset to gauge environmental quality. Furthermore, this research delves deeply into the transmission mechanisms and relationships among green innovation, renewable energy consumption, economic growth, population, and environmental degradation within BRICS countries. In terms of methodology, this study employs the threshold model to explore the associations between these variables.

3. Theoretical framework and hypothesis development

The IPAT model, which is an accounting equation, has been found to have certain limitations. One such limitation is that it is not suitable for statistical analysis, as statistical associations do not necessarily indicate causal relationships. Additionally, the model is unable to account for the non-proportional effects of the variables. These drawbacks have been highlighted by Refs. [36–38]. In order to address these limitations [37], created the Stochastic Regression on Population, Affluence, and Technology (STIRPAT) model, which enables the empirical testing of hypotheses. The following equation shows the specifications of the STIRPAT model:

$$I_i = \propto P_i^{\beta} A_i^{\gamma} T_i^{\delta} \varepsilon_i \tag{1}$$

in above equation (1), *P* represents population, *A* represents affluence measured by *GDP* per capita, and *T* is technology or innovation. However, β, γ, δ are the parameters. But in the present study, we checked the impact of renewable energy consumption (*RE*), green innovation (*GI*), economic growth (*GDP*) and population (*POP*) on environmental degradation (*EFT*). Then, equation (1) becomes:

$$EFT_i = \propto POP_i^{\beta} GDP_i^{\gamma} GI_i^{\delta 1} RE_i^{\delta 2} \varepsilon_i \tag{2}$$

3.1. Theoretical mechanism of the study

This section of the study explains the transmission relationships and underlying mechanism among green innovation, renewable energy, economic growth, population, and environmental degradation across BRICS countries.

3.1.1. Renewable energy consumption, green innovation and environmental degradation

The core objective of this study is to investigate the effect of *RE* consumption on environmental degradation, mediated by the threshold effect of *GI* [39]. highlighted the potential of widespread *RE* technology adoption to boost economic growth among G7 countries. Conversely [40], argue that the expansion of *RE* can positively influence environmental quality, suggesting a reciprocal relationship in ASEAN countries [41]. suggest that *RE* implementation can enhance production capabilities within enterprises due to reduced energy costs, incentivizing firms to embrace innovative technology and creative practices. Likewise [42], finds that *RE* consumption can benefit companies by increasing *GI*. In their study [43], employed a dynamic panel data model and regional-level data from 1995 to 2012 in China to explore the relationship between energy consumption and technological innovation, affirming the enduring link between energy use and technological progress. More recently [44], investigated the dynamics of innovation in green energy, unveiling the interplay between energy intensity and *GI* activities in both the short and long term [45]. suggest that *GI* implementation can effectively mitigate shadow economic activities and promote sustainable development.

Based on existing research, it can be inferred that the adoption of *RE* positively impacts a country's *GI* potential, leading to a reduction in environmental degradation. However, it is imperative to delve into the threshold effect of *GI* at which *RE* influences environmental degradation. Fig. 2 provides a theoretical framework illustrating the intricate relationship between *RE*, *GI*, and environmental degradation (*EFT)*. Consequently, we formulate the first hypothesis of the study as follows:

H1. RE indirectly affects environmental degradation through the threshold effect of GI.

3.1.2. Economic growth, green innovation and environmental degradation

A growing body of scholarly work underscores the pivotal role of economic development as a catalyst for *GI* [15,46,47]. [48] emphasize *GI's* potential in addressing pressing environmental concerns by fostering novel processes that contribute to energy conservation, waste reduction, pollution mitigation, and environmental preservation [49]. highlights the advantages and significance of economic development, asserting that anticipated economic growth can catalyze the globalization of *GI*. They posit that a larger market size facilitates the adoption of advanced technological innovations, leading to increased investment in *GI* development.

Moreover, research by Ref. [50] suggests that national objectives aimed at economic expansion can influence resource allocation, subsequently impacting *GI* [51]. employed the bootstrap autoregressive-distributed lag (BARDL) approach to examine the relationship between economic growth and *GI* in Singapore. They found a positive association between these variables. However [52,53], posit that an intensification of economic development objectives could adversely affect *GI*. This negative impact was also found by Ref. [54], and the study attributed this impact to the tendency to prioritize quantity over quality in the pursuit of economic growth objectives. Furthermore, regions that have already achieved their economic growth targets experience a gradual decrease in *GI*. Conversely, regions that have not yet reached their objectives show a negligible impact. Based on these studies, a positive relationship between economic development and *GI* emerges, suggesting a potential reduction in environmental degradation. However, it is crucial to determine the threshold effect of *GI* that influences the relationship between *GDP* and environmental degradation. Fig. 2 presents a theoretical framework delineating the interplay between *GDP*, *GI*, and environmental degradation. In light of the above, we propose the following hypothesis:

H2. GDP indirectly affects environmental degradation through the threshold effect of GI.

3.1.3. Population, green innovation and environmental degradation

The existing scholarly literature concerning the direct correlation between *POP* and *GI* remains limited. Nevertheless, valuable insights can be gleaned from the available research. The concept of a social catastrophe, initially proposed by Malthus, raised questions about the potential consequences of exponential population growth, increased resource consumption, and expanded subsistence on society. In a similar context [8], highlights that population affect the environment through two primary mechanisms: resource consumption (including land, food, water, air, fossil fuels, and minerals) and waste generation (comprising air and water pollutants, hazardous compounds, and greenhouse gases resulting from human activities). Recent research by Ref. [55] indicates that *POP* exerts a noteworthy and favorable influence on corporate *GI*, particularly among small and medium-sized firms (SMEs) and state-owned enterprises (SOEs). This suggests that a larger population leads to increased *GI*, subsequently resulting in reduced environmental degradation. However, given the scarcity of studies addressing this specific aspect, further investigation is imperative. Fig. 2 illustrates the theoretical process elucidating the interplay between *POP*, *GI*, and environmental degradation. Consequently, we propose the following hypothesis:

H3. POP indirectly affects environmental degradation through the threshold effect of GI.

It is essential to note that this research encompasses two key dimensions: (1) examining the linear impact of *GI*, *RE*, *GDP*, and *POP* on environmental degradation, and (2) analyzing the indirect effect based on the threshold effect of *GI*.

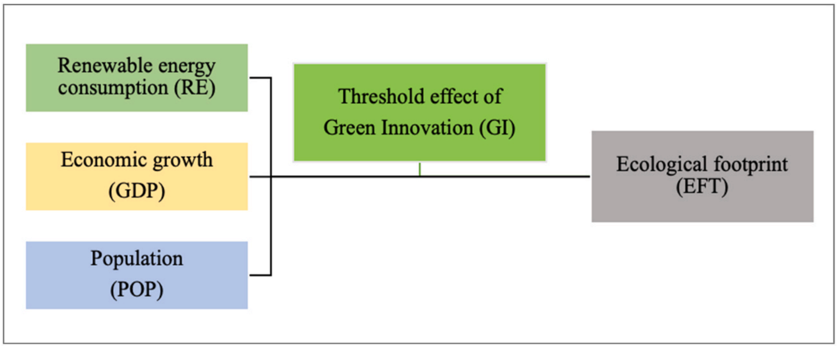

Fig. 2. Theoretical mechanism of the study.

4. Data and methodology

4.1. Data and source of variables

The study investigates how green innovation affects environmental deterioration in BRICS countries for the period 1992–2021. Table 1 below displays the details of the data and relevant variables. We used the logarithm form of all the variables to ensure that the data are smooth, to reduce the impacts of heteroskedasticity and autocorrelation, and to avoid false regressions.

4.2. Baseline regression model

We developed the following empirical model to gauge the effect of *GI* on environmental degradation in order to assess the applicability of the STIRPAT[4] model for BRICS countries:

$$LEFT_{it} = \alpha_1 LGI_{it} + \alpha_2 LRE_{it} + \alpha_3 LGDP_{it} + \alpha_4 LPOP_{it} + \varepsilon_{it} \tag{3}$$

in the above equation, $LEFT_{it}$ represents ecological footprint measure of environmental degradation in every country in the corresponding year, LGI_{it} depicts green innovation measured by environment-based technology, LRE_{it} is the use of renewable energy by each country, $LGDP_{it}$ represents degree of the economic growth, and $LPOP_{it}$ is the population growth in each country.

4.3. Cross-sectional dependence and unit root test

In the study of panel data models, determining cross-sectional dependency (CD) is essential. In order to assess the CD in the data, the [56] test was performed. When the CD analysis is ignored, the findings may not be reliable. The Pesaran CD test appears as follows:

$$CD = \sqrt{\frac{2T}{M(M-1)}} \sum_{i=1}^{M-1} \sum_{p=i+1}^{M} \rho_{pi} \tag{4}$$

In the above equation, time is represented by T, the size of the panel data is represented by M, and correlation coefficient is represented by ρ_{pi}. Accepting the null hypothesis suggests that there is no CD, whereas rejecting it means that CD exists. To address the CD issue, Cross-sectionally IPS (CIPS) test is employed. It is mathematically written as:

$$CIPS = \frac{1}{N} \sum_{i=1}^{N} CADF \tag{5}$$

4.4. Westerlund (2007) cointegration test

The [19] cointegration test is used in this study to examine the relationship between the variables in the long-term. The [19] test yields accurate findings even in the presence of CD. The [19] method tests the null hypothesis that there is no cointegration based on two-panel and two-group statistics using the equation below:

$$\Delta Y_{it} = \rho d_t + \varnothing_i \left(Y_{i,t-1} - \beta_i x_{i,t-1}\right) + \sum_{j=1}^{\delta_i} a_{ij} \Delta Y_{i,t-j} + \sum_{j=q}^{\delta_i} \tau_{ij} \Delta x_{i,t-j} + \mu_{it} \tag{6}$$

[4] STIRPAT model tests the impact of technology, affluence and population growth on the environment. It is represented as follows.

$$I = P + A + T$$

Table 1
Description of variables.

Variable name	Symbol	Measurement	Source
Ecological Footprint	EFT	Ecological footprint in global hectares	GFN
Green Innovation	GI	Environmental related patents (% total patents)	OECD
Renewable energy	RE	Renewable energy consumption (% of total energy consumption)	IEA
Economic growth	GDP	Gross domestic product per capita (constant 2015 US$)	WDI
Population	POP	Total population	WDI

4.5. Augmented mean group (AMG) model

A significant body of research has recently started to focus on the CD of regression models and to emphasize the value of econometric approaches that take this component into account. This is crucial since the majority of conventional panel econometric approaches do not account for CD. According to Ref. [57], the CCE-MG method cannot be used in lieu of the AMG estimator since it uses the common dynamic process to account for CD in country regressions. This approach provides panelists with various slope coefficients and takes CD into account. Since it weights the co-integration coefficients to get their arithmetic mean, this estimate approach is also more reliable than others. In light of this, we may calculate the coefficients of the benchmark model using the augmented mean group (AMG) estimator. The AMG estimator handles serial correlation and endogeneity in two phases using temporal dummy variables and dynamic functions:

$$\Delta y_{it} = \alpha_i + \beta_i \Delta X_{it} + \sum\nolimits_{t=2}^{T} \delta_i D_t + \rho_i F_t + \epsilon_{it} \tag{7}$$

In the above equation, Δ is the first-order difference operator and D_t represents the time dummy variable.

4.6. Panel threshold regression model

This study employs a panel threshold model to investigate the threshold impact of green innovation (*GI*) on environmental degradation within the BRICS countries. Introduced by (Hansen, 1999), the threshold model offers insights into how economic parameters change direction when another parameter crosses a specific threshold level. To ascertain the presence of a threshold effect, a bootstrap-based test is applied under the null hypothesis that none exists. A noteworthy advantage of the panel threshold model lies in its ability to capture both cross-sectional heterogeneity and time series dynamics, as emphasized by Ref. [13]. This unique feature enhances the precision of estimating the relationships between variables. In contrast to conventional linear regression models, the panel threshold model excels at revealing nonlinear correlations between dependent and independent variables. This nuanced approach enables a more comprehensive understanding of the complex interplay between these factors. The regression of the panel threshold model is written as follows:

$$\begin{aligned} LEFT_{it} = {} & \delta_i + \beta_1(LGI_{it} \le \gamma_1) + \beta_2(LGI_{it} > \gamma_2) + \beta_3 LRE_{it}(LGI_{it} \le \gamma_1) + \beta_4 LRE_{it}(LGI_{it} > \gamma_2) + \beta_5 LGDP_{it}(LGI_{it} \le \gamma_1) \\ & + \beta_6 LGDP_{it}(LGI_{it} > \gamma_2) + \beta_7 LPOP_{it}(LGI_{it} \le \gamma_1) + \beta_8 LPOP_{it}(LGI_{it} > \gamma_2) + \varepsilon_{it} \end{aligned} \tag{8}$$

In the above equation (6), *LGI* is the threshold variable and γ_1 and γ_2 are the threshold parameters. δ_i captures the country-specific effects, γ is the threshold level of *LGI* and displays if the numbers are higher than or lower than the threshold level. In this way, this study establishes that *LGI* must reach a particular level of use in order to lessen environmental deterioration.

5. Results and discussion

5.1. Cross-sectional dependence test results

The need to authenticate the existence of cross-sectional dependence (CD) has become critical due to macroeconomic shocks. This study used panel data analysis; hence, there is a chance that CD problems may arise. Given that we have T < N, this inquiry employed the [58] CD test, and the results are shown in Table 2. The CD-statistic for each variable rejects the null hypothesis that there is no CD at

Table 2
Cross-sectional dependence test.

Variable	CD-statistic	p-value
LEFT	−2.23**	0.03
LGI	−2.79**	0.02
LRE	−4.26***	0.00
LGDP	−4.49***	0.00
LPOP	−7.94***	0.00

Note: ** & *** indicates significance at 5 % & 1 % level.

a 1 % level of significance. Hence, CD exists because a shock that occurs in one of the sample countries may spread to the others.

5.2. CIPS unit root test results

To prevent erroneous findings, the stationarity of the variables must be verified once CD has been confirmed to exist [59]. The CIPS test recommended by Ref. [58], which addresses the problem of CD and slope heterogeneity, is suitable to apply. Table 3 demonstrates the results of the CIPS test and confirms that all variables are integrated of order I (1).

5.3. Westerlund (2007) cointegration test results

Having established that all the variables are stationary at the first difference, the next step is to examine the possibility of cointegration among them. To conduct this investigation, we employ the Westerlund cointegration test, which relies on cross-sectional interdependencies across countries. The outcomes of the Westerlund test, as presented in Table 4, provide compelling evidence of a long-run relationship among the variables.

5.4. The AMG estimation results

The results of the AMG estimation are presented in Table 5. Notably, the coefficient for *LGI* stands at −0.042, signifying that innovation has an adverse impact on the environment within BRICS countries. This finding is consistent with prior research conducted by Refs. [1,60,61], which suggests that green innovation has contributed to a reduction in environmental degradation in both OECD and BRICS countries. Similarly, the influence of *LRE* is found to be negative and statistically significant at the 5 % level. Specifically, a 1 % increase in the *LRE* is associated with a 0.158 % decrease in the *LEFT*. These outcomes indicate that renewable energy consumption exerts a positive influence on mitigating environmental degradation, aligning with the findings of [6,18]. These studies demonstrate that the adoption of renewable energy, considered a cleaner alternative to nonrenewable energy sources such as fossil fuels, leads to a reduction in *LEFT*.

However, the analysis reveals that economic growth (*LGDP*) is accelerating environmental damage. A 1 % increase in *LGDP* corresponds to a substantial 39.6 % increase in *LEFT*, consistent with recent research by Refs. [7,13]. This phenomenon can be attributed to the decline in air quality and the heavy reliance on nonrenewable resources like fossil fuels, a significant source of air pollution, during the initial stages of economic growth. Furthermore, the empirical findings indicate a positive association between population growth (*LPOP*) and environmental degradation (*LEFT*). At the 10 % significance level, population expansion is strongly linked to environmental degradation. BRICS countries, marked by rapid industrialization, population growth, and economic development, tend to leave a larger environmental footprint. Consequently, it becomes evident that countries with larger populations often grapple with serious challenges related to environmental sustainability, as observed in studies by Refs. [62,63].

5.5. The threshold effect test results

Before embarking on an investigation using a threshold model, it is imperative to ascertain the presence of threshold effects and determine the appropriate number of thresholds. This process involves a series of tests. Initially, a single threshold test is conducted, where the null hypothesis posits the absence of any thresholds. If this null hypothesis is not accepted, a second threshold test follows. If the null hypothesis is rejected once more, a third threshold test, and so forth, can be carried out. Table 6 illustrates the results of our analysis when *GI* serves as the threshold variable. The outcomes indicate a clear threshold effect. Notably, our model passed both the single threshold test and the double threshold test, thereby implying that the null hypothesis proposing the inclusion of two threshold values cannot be dismissed. Specifically, the p-value associated with the triple threshold test is 0.446, meaning that only two thresholds are present. Fig. 3 provides a visual representation of the likelihood ratio trend, which further supports this conclusion. The likelihood ratio statistics for the two threshold values are smaller than the critical values at the 95 % significance level, conclusively establishing the existence of a double threshold within the model.

Table 3
CIPS unit root test results.

Variable	Statistic		Decision
	Level	1st Diff	
LEFT	−1.701	−5.332**	I(1)
LGI	−1.275	−5.311**	I(1)
LRE	−0.561	−4.892**	I(1)
LGDP	−0.714	−3.364**	I(1)
LPOP	−1.941	−4.938**	I(1)

Note: ** significant at 5 % level.

Table 4
Westerlund (2007) ECM panel cointegration results.

Statistic	Value	Z-value	*P*-value
G_t	−1.698	−1.733	0.042
G_a	−4.364	1.534	0.938
P_t	−10.31	−3.709	0.000
P_a	−4.833	−2.735	0.003

Note: H_0 = No cointegration.

Table 5
AMG model results.

Variable	Coefficient	Std. error	z-value	P > Z
LGI	−0.042***	0.181	2.35	0.019
LRE	−0.158**	0.075	2.10	0.042
LGDP	0.396*	0.204	1.94	0.053
LPOP	1.236*	0.677	1.82	0.068
C	2.821***	1.140	2.47	0.013

Note: ***,** & * indicates significance at 1 %, 5 % & 10 % level.

Table 6
The threshold effect test.

Threshold	F-statistic	p-value	10 %	5 %	1 %
Single	78.93*	0.106	78.72	87.99	115.66
Double	88.73*	0.080	82.23	95.64	120.14
Triple	44.58	0.446	117.53	155.70	203.61

Note: Author's calculations.

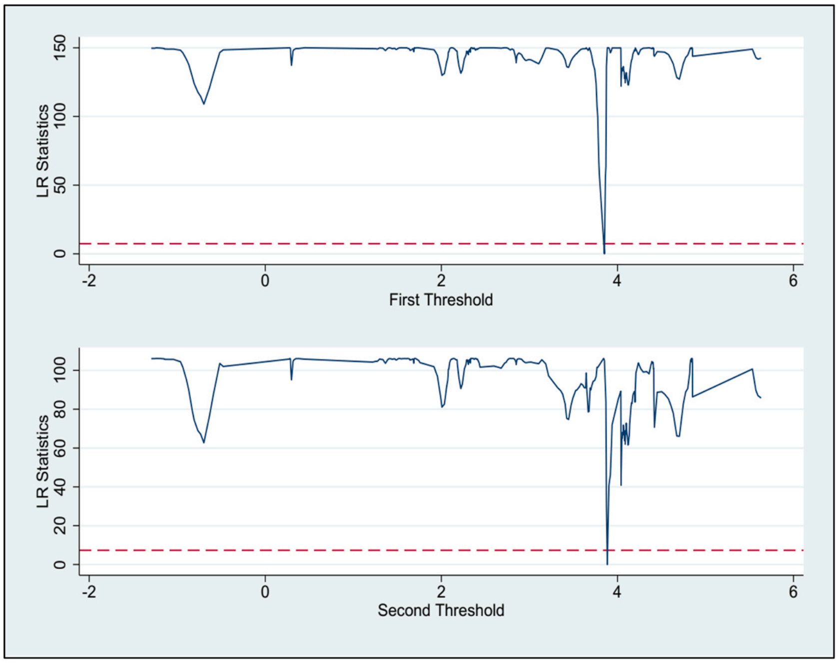

Fig. 3. Graphical representation of the threshold effect test.

Table 7
Panel threshold model results.

Variable name	Coefficient	Std.error	*p*-value
C	5.116***	0.603	0.00
$LGI_{it} \leq \gamma_1$	0.306**	0.135	0.02
$LGI_{it} > \gamma_2$	−0.513***	0.144	0.00
LRE_{it} ($LIEQ_{it} \leq \gamma_1$)	0.241	0.167	0.15
LRE_{it} ($LIEQ_{it} > \gamma_2$)	−2.495***	0.266	0.00
$LGDP_{it}$ ($LIEQ_{it} \leq \gamma_1$)	0.397***	0.140	0.00
$LGDP_{it}$ ($LIEQ_{it} > \gamma_2$)	−0.744***	0.133	0.00
$LPOP_{it}$ ($LIEQ_{it} \leq \gamma_1$)	0.820***	0.172	0.00
$LPOP_{it}$ ($LIEQ_{it} > \gamma_2$)	−1.435***	0.236	0.00

Note: F test that all $u_i = 0$: F (6, 951) = 43.47, Prob > F = 0.00.
Author's calculations.

5.6. The panel threshold model estimation results

The results of the panel threshold model are shown in Table 7. The result implies that the value of *LGI* is negative. Since *LEFT* rises by 0.306 % when *LGI* is below the threshold level and falls by 0.513 % when *LGI* is above it. *LGI* initially causes a rise in *LEFT* due to energy use and the recycling of electronic waste. But at a high level, it is predicted to cause a fall in *LEFT* due to the implementation of smart cities, hybrid transportation systems, *RE* sources of electricity, and energy-efficiency production methods. The results of prior research by Refs. [1,15,61,64] are consistent with our findings. For instance, increased energy efficiency in other sectors like transportation, building, and power may improve *LGI*. Therefore, based on our research, green innovation seems to have a positive effect on the environmental sustainability. The effect of *RE* is favorable; when *LGI* levels are below the threshold level, *LEFT* increases by 0.241 %, and when *LGI* levels are above the threshold level, *LEFT* decreases by 2.495 %. Based on these findings the first hypothesis (H1) of the study is accepted that there is indirect effect of *LRE* on environmental degradation through threshold effect of *LGI*. The reason is that initially energy use and the recycling of electronic waste *LRE* have no effect, but somehow have a harmful effect due to the use of nonrenewable energy sources. But after the completion of *RE* projects like hybrid transportation systems, hydroelectricity, and energy-efficient techniques of production, it lowers *LEFT* and improves environmental quality.

When the *LGI* is below the threshold level, the coefficient value of *LGDP* is 0.397; when the *LGI* is above the threshold level, it climbs to 0.744 but has a detrimental effect on *LEFT*. Here, the second hypothesis (H2) of the study is accepted that there is indirect effect of *LGDP* on environmental degradation through threshold effect of *LGI*. This shows that the scale effect causes an initial increase in CO2 emissions, although compositional and technological improvements may provide an improvement in the environment at high income levels. These results are also supported by the findings of [7,13,65]. The development of science and technology were ignited by the increase in income levels, as can be seen from the development processes and experiences of many countries. The modern, technology-intensive technologies and industries described below have replaced the outdated, capital- and labor-intensive ones that were associated with high emissions, high energy consumption, and high pollution. Economic growth first caused a reduction in environmental quality, but the influence of technology and structural changes reversed this trend, and as pollutant emissions progressively reduced, the quality of the environment also increased.

Now, when *LGI* is below the threshold level, an increase in *LPOP* of one percentage point causes an increase in *LEFT* of 0.820 % in terms of population. However, when *LGI* exceeds the threshold level, the effect of *LPOP* on *LEFT* increases to 0.1.435 %. It is found that the coefficient of *LPOP* is positive, whether the *LGI* level is above or below the threshold. Hence, the third hypothesis (H3) of the study is accepted that there is an indirect effect of *LPOP* on environmental degradation through the threshold effect of *LGI*. The coefficient value of *LPOP* (0.820) demonstrates that, in the absence of *LGI*, growing *LPOP* produces the scale effect and that *LPOP* growth results in carbon emissions as a result of elevated energy consumption. However, the lower value of the coefficient of *LPOP* (−1.435) given to the *LGI* over the threshold level demonstrates that the *LGI* supports economies in the transition to smart cities with energy-efficient technologies and promotes low-emission infrastructures, which subsequently improves the quality of the environment in urban areas. The positive coefficient of *LPOP* is in accordance with the priori expectations and the results of [66–69].

6. Conclusion

The analysis of the study is carried out using a panel of BRICS countries over the years 1992–2021. The novel aspect of the study is that it explores the transmission relationship and mechanism among renewable energy consumption, economic growth, population, and environmental degradation based on the threshold effect of green innovation in BRICS countries. In this particular research, a broad variety of estimation methods are used that take into account cross-sectional dependency (CD) and heterogeneity issues. These methodologies included the CIPS panel unit root test, the [70] CD test, the Westerlund (2007) cointegration test, the AMG model, and the panel threshold model. The results of this investigation led the researchers to the conclusion that expanding the use of green innovation would result in a lower rate of environmental degradation. However, the results also demonstrate that this objective will not be accomplished over the course of time until a particular threshold level of green innovation is reached. The rate of environmental degradation may begin to level off after a particular level of green innovation is reached, and it may finally come to a complete halt.

Based on the findings, our recommendations for policymakers and stakeholders in BRICS countries are to promote renewable energy and drive green innovation. For this purpose, green innovation initiatives should be prioritized in addition to improving the effectiveness of new technology and the infrastructure associated with it. Moreover, investing in renewable energy reduces the dependence of BRICS countries on fossil fuels, leading to more stable energy prices and reduced exposure to price volatility in global oil and gas markets. Secondly, BRICS countries should invest more in renewable energy because there is an incentive for companies and research institutions to innovate. This can lead to advancements in green technologies, making them more efficient and cost-effective. BRICS countries, especially China, have the potential to become major exporters of green technologies, providing them with a competitive edge in the global market. Third, BRICS countries should adopt policies and incentives that will strengthen the relationship between economic growth and green innovation. Because green innovation driven by economic growth will further promote environmental sustainability. Last but not least, the benefits and drawbacks of green innovation should thus be balanced in a manner that is more environmentally responsible.

7. 6.1 Limitations and future recommendations

The present study has certain limitations. It primarily focuses on investigating the mechanisms of renewable energy consumption, economic growth, and population and their impact on environmental degradation, with a specific emphasis on the threshold effect of green innovation within BRICS countries. To expand upon this research, future studies could benefit from utilizing panel data encompassing a broader spectrum of countries and encompassing members of prominent international organizations such as the OECD, G-20, G-7, and the European Union. Additionally, an intriguing avenue for further investigation would involve conducting research at the regional level. This approach would allow for an in-depth examination of the threshold effect of green innovation on environmental degradation in both high- and low-income countries. Moreover, it could shed light on the varying effectiveness of green innovation initiatives across different income brackets.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Consent to participate

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CRediT authorship contribution statement

Biao Geng: Formal analysis. **Guojun Yuan:** Writing – review & editing. **Daoning Wu:** Resources, Writing – review & editing. **Samia Khalid:** Conceptualization, Data curation. **Hamid Mahmood:** Formal analysis, Methodology, Software.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Biao Geng reports financial support was provided by West Anhui University **People's Republic of China (PRC)**. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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