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The relevance of renewable energy and green innovation in environmental sustainability: evidence from BRICS countries

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Abstract: The study examines the significance of green innovation and renewable energy usage in reducing the carbon and ecological footprints in Brazil, Russia, India, China, and South Africa (BRICS) countries. It applies a series of econometric techniques and the Driscoll-Kraay standard errors regression approach to data collected between 1995 and 2018 based on the environmental Kuznets curve (EKC) hypothesis. Important macroeconomic control variables, such as industrialisation, urbanisation, financial development, trade openness, and natural resources, are also used to strengthen the model. Empirical results show that a 1% increase in green innovation reduces the carbon and ecological footprint by 0.229% and 0.226%, respectively. Further, increasing renewable energy consumption by 1% decreases the carbon and ecological footprints by 0.024% and 0.032%, respectively. Furthermore, the empirical findings support the EKC hypothesis. The study has important policy implications for governments and policymakers of emerging countries to invest more in green innovation and promote renewable energy.

Keywords: green innovation; renewable energy; carbon footprint; ecological footprint; BRICS; Driscoll-Kraay standard errors; environmental Kuznets curve; EKC; environmental degradation; GDP; economic growth.

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1 Introduction

Research shows that greenhouse gas (GHG) emissions worsen environmental sustainability and trigger global warming (Hove and Tursoy, 2019; Burki and Tahir, 2022; Kar, 2022; Ozili, 2022). The Intergovernmental Panel on Climate Change (IPCC, 2018) report notes that GHGs are increasing at a 1.5% yearly rate, and elevated carbon dioxide (CO₂) emissions are one of the primary causes of global warming. These emissions also harm the environment and have negative economic implications (Ahmad et al., 2019). Environmental degradation (ED) causes poverty, spreads infectious diseases, causes extreme weather, and has a long-term impact on ecological biodiversity (WHO, 2019). Again, according to the World Wild Fund (WWF, 2018) report, although there has been a 27% increase in global biological capacity over the previous 50 years, the ecological footprint has expanded by 190%. Because of this disparity between biocapacity and ecological footprint, the earth is seeing alarmingly rising temperatures and adverse climatic conditions in numerous locations.

Biologically productive area or biocapacity is the ecosystems' ability to regenerate what people demand from those surfaces (Wackernagel et al., 2019). The ecological footprint is the amount of biologically productive land and water required by an individual, population, or activity to produce all the resources it consumes and absorb the waste it creates utilising current technology and resource management methods (Rees, 1992; Wackernagel and Rees, 1996). The difference between biocapacity and ecological footprint is known as ecological deficit/surplus. The carbon footprint estimates CO₂ emissions caused by the use of fossil fuels. These amounts are transformed into biologically productive areas required for CO₂ absorption in ecological footprint accounts (Mancini et al., 2016). Here the ecological footprint is an inclusive indicator based on cropland, grazing land, fishing grounds, built-up land, forest area, and carbon footprint demand on land by human-being (Lin et al., 2018). Thus, the ecological footprint includes the carbon footprint as a major component (Bello et al., 2018). "Ecological footprint and biocapacity are usually expressed in units of world average bioproductive area, referred to as global hectares (gha)" [Borucke et al., (2013), p.521].

Rising CO₂ emissions are a severe issue for the economies of the Brazil, Russia, India, China, and South Africa (BRICS), which suffer ED issues despite extensive natural resources and robust economic performance (Aydin and Turan, 2020). Again, rapid economic development in emerging nations increases investment opportunities and boosts energy demand, harming the environment. Many economists and academicians believe that human activities resulting from industrialisation, product diversification, and economic expansion are the most significant source of CO₂ emissions (Esmaeili et al., 2023). Many emerging nations struggle to increase economic growth without

implementing significant environmental sustainability measures. As a result, these economies have a trade-off between economic growth and environmental sustainability (Anwar et al., 2022b; Liu et al., 2022a). Even the effects of unplanned economic growth on the environment have attracted the attention of the global economy, which can be seen in the Paris Agreement of 2015 and the Kyoto Protocol of 1997 (Kim et al., 2020). Many studies found that economic growth and energy consumption are severe concerns for environmental deterioration. Therefore, countries are investing in technologies to switch from conventional to green or renewable energy sources to address the increasing energy demand (Danish et al., 2020). Renewable energy sources include the energy generated from wind, solar, waves, tides, and geothermal heat, which helped to reduce ED during the past few decades (Cheng et al., 2019).

In recent years, many researchers have emphasised the advancement of green innovation as an effective tool for achieving sustainability goals, improving energy efficiency, reducing the adverse effects of resource use, and decreasing pollution and other environmental risks (Mongo et al., 2021). The Sustainable Development Goals (SDGs) progress report also emphasised the importance of green innovation and substantially increased the share of renewable energy to meet SDGs. Recent studies by Anwar et al. (2022a, 2023) and Liu et al. (2022b) have emphasised the role of technological innovation in achieving the SDGs by combating CO₂ emissions. Despite the rising trend of renewable energy, consumption is still limited in many nations due to relatively high costs and other technological challenges (Chen et al., 2014). New environmentally friendly green technology developments can significantly contribute to combating all ED challenges (Liu et al., 2022a). Green innovation includes breakthroughs in pollution control, energy conservation, waste recycling, and environmental management (Huang et al., 2019). Green innovation is a potential option for reducing carbon emissions and ecological footprint since it incorporates eco-friendly technologies into existing processes to achieve maximum growth at the lowest possible environmental cost (Shao et al., 2021; Umar et al., 2020).

Thus, the study's primary purpose is to explore the claim that green innovation and renewable energy consumption help improve environmental quality under the environmental Kuznets curve (EKC) framework in the panel of the five emerging nations, that is, BRICS. This study has considered carbon footprint and ecological footprint as indicators of ED to study their relationship with green innovation, renewable energy consumption, and other major macroeconomic determinants.

The present study draws empirical evidence only on the BRICS countries for the following reasons.

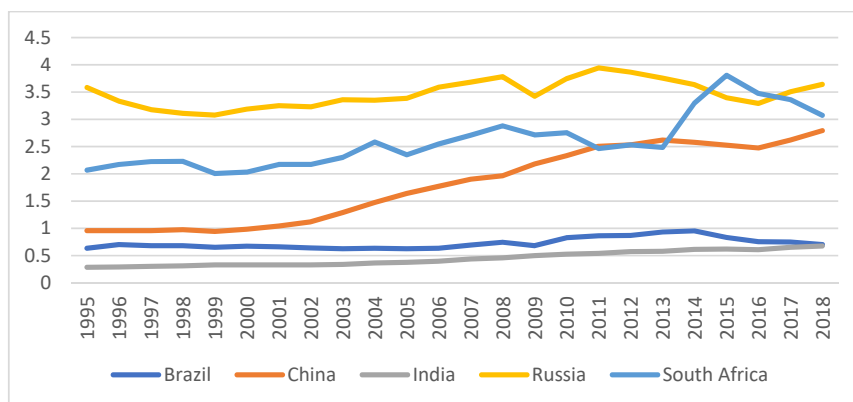
- 1 Like many other emerging economies, BRICS witnessed a quick transition from ecological surplus to ecological deficit, mainly owing to the region's exceptional growth over the last decade (Nathaniel et al., 2021). Figures 1 and 2 provide the details of each BRICS country's per capita carbon footprint and ecological footprint, respectively. Here, the per capita footprint is calculated by dividing the total footprint of the country by its total population. Among the BRICS countries, the highest per capita carbon and ecological footprints are for Russia, and the lowest is for India. From Figure 2, we can see that all five countries are in a situation of ecological deficit. That means they are demanding more on the earth's natural resources.

- 2 Their GDP is roughly 23% of the world's GDP, with 19.851 trillion dollars, 26% of the geographical area, and 41.50% of the world population in 2020 (Aydin and Turan, 2020). Also, they consume more than 40% of global energy, making them a significant source of global CO₂ emissions (Lin et al., 2021).
- 3 According to the New Development Bank (NDB) report of 2016, to achieve sustainable development, BRICS nations have developed their Intended Nationally Determined Contributions (INDC) and plan to generate a significant portion of their power from renewable sources (NDB, 2016). Across various periods (up to 2030), the BRICS countries want to increase their total installed renewable energy capacity to 1,251 Gigawatt (GW). China and India have the highest renewable capacity expansion targets, with 253 GW by 2020 and 138 GW by 2022, respectively (Lin et al., 2021).

The study will contribute to the research field in the following ways. First, to the best of the authors' knowledge, this is the first study to investigate the simultaneous impact of green innovation and renewable energy consumption on environmental deterioration in BRICS countries. Also, by following previous research, the study tests the impact of urbanisation, industrialisation, financial development, natural resources, and trade openness on ED. The inclusion of all these control variables strengthens the estimated model and differentiates the study from earlier studies.

Second, to capture ED, the study uses two proxies, namely, carbon footprint and ecological footprint, which are considered better indicators of environmental sustainability than emission-based indicators (Solarin, 2019; Bello et al., 2018). The study tests the validity of the EKC hypothesis based on these two measures of ED. The use of footprint as a measure of ED has great relevance for BRICS countries because they are developing, and there is an ecological deficit in these countries (Nathaniel et al., 2021).

Figure 1 Trend line of per capita carbon footprint (see online version for colours)

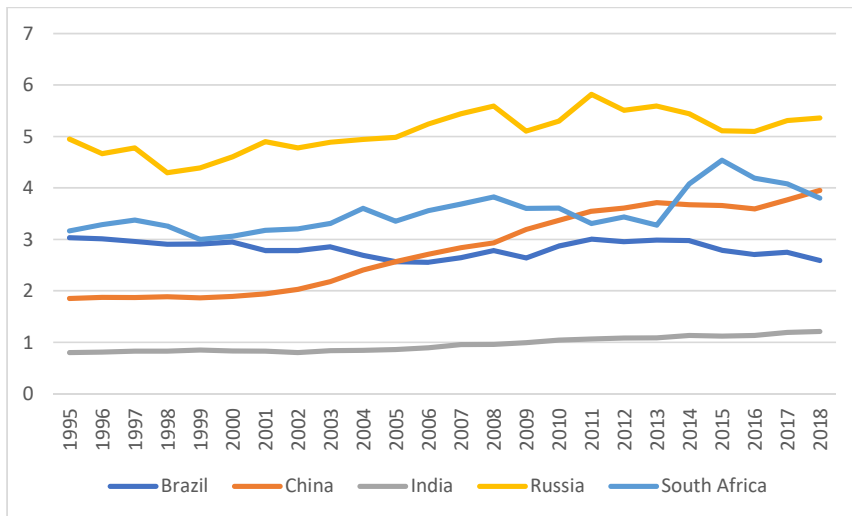


Source: GFN (2021)

Third, the study uses multiple econometrics techniques, and the Driscoll-Kraay standard error panel estimates to test the hypothesis. It is a robust econometric technique that overcomes cross-section dependence and problem heterogeneity (Danish and Ulucak, 2020). Further, by following Cai et al. (2022), the study also uses the fully modified least

squares (FMOLS) analysis to check the robustness of our study's result. Fourth, based on the results, the study suggests policy implications for the government and policymakers to achieve a greener and more sustainable economy.

Figure 2 Trend line of per capita ecological footprint (see online version for colours)



Source: GFN (2021)

The remaining part of the paper is organised as follows. Section 2 presents a recent literature review; Section 3 provides the methodology used in the study, which includes the data sources, model specification, and econometric techniques; Section 4 presents the discussion of the results obtained; Section 5 presents the conclusion of the study and policy implications.

2 Literature review

2.1 Theoretical framework

The study intends to investigate the influence of green innovation and renewable energy consumption in mitigating ED in the EKC hypothesis framework. Inspired by Kuznets' inverted-U-shaped income distribution curve, Grossman and Krueger (1991) suggested the EKC hypothesis, which posits that there may be an inverted-U-shaped association between environmental deterioration and economic expansion. The theory states explicitly that ED is an increased action of the degree of economic activity up to a particularly critical stage of income or turning point from which higher income levels are connected with progressively higher levels of environmental quality (Numan et al., 2022). Grossman and Krueger (1991) showed in their study that economic development affects environmental quality differently in each of the three stages of economic expansion. Due to scale effects, demand for natural resources such as land for economic activities grows in the early phase, harming the environment. Thus, the scale effect represents the rising part of an inverted U-shaped EKC. As a result of composition

effects, the second phase of the inverted-U-shaped EKC signifies a pivotal moment where the economy's structure begins to alter, and the country begins to prioritise environmentally friendly economic activity. In the third phase, the country replaces outdated technology with more environmentally friendly ones in manufacturing processes, illustrating the falling component of the inverted-U-shaped EKC.

2.2 Empirical evidence

2.2.1 Relationship between economic growth and ED

Following the pioneering work of Grossman and Krueger (1991), numerous scholars have researched the validity of the EKC for various nations or country groups. Furthermore, some academics have highlighted the significance of economic growth as a central determinant of ED based on the EKC hypothesis. A vast number of empirical research undertaken in various parts of the world demonstrates the significance of EKC and its policy implications. Although the research is divided on this topic, is the EKC interaction a myth or a reality? Most of the research experimentally validates the EKC hypothesis and claims that it may be utilised for any policy implications (Balsalobre-Lorente et al., 2022; Bilgili et al., 2021; Burki and Tahir, 2022; Cai et al., 2022; Castiglione et al., 2012; Danish et al., 2020; de Souza et al., 2018; Dogan et al., 2019; Farooq et al., 2021; Ganda, 2018; Gopakumar et al., 2022; Gupta et al., 2022; Harrathi and Almohaimeed, 2022; Khan et al., 2022; Lorente and Alvarez-Herranz, 2016; Sarwat et al., 2022). In contrast, some studies rejected the validity of the EKC hypothesis and suggested that any policy based on the hypothesis may not be appropriate in practice (Ali et al., 2017; Cosmas et al., 2019; Dogan et al., 2020; Hove and Tursoy, 2019; Kar, 2022; Li et al., 2022b; Linh and Lin, 2014; Mehmood, 2022; Nawaz et al., 2021).

Murshed et al. (2022) found statistical evidence to validate the EKC hypothesis in a panel of five South Asian countries using carbon and ecological footprint to indicate environmental quality. But the country-specific results in this regard did not validate the EKC hypothesis for Pakistan and validated for Bangladesh, India, Nepal, and Sri Lanka. These contradictory results can be categorised depending on factors such as methodology, data sources, environmental indicators, and the reliability of computed coefficients. In a recent study, Esmacili et al. (2023) validated the existence of the EKC hypothesis in the case of Next-11 (Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, South Korea, Turkey, and Vietnam) countries, where they found the positive impact of the economic complexity index on CO₂ emission and the negative impact of the squared term of economic complexity index on CO₂ emission. Similarly, the present study attempts to validate the EKC hypothesis in the case of BRICS countries by considering two different proxies of ED, namely, carbon footprint and ecological footprint. Hence, the first hypothesis of the study is,

Hypothesis 1 EKC exists in the case of BRICS countries concerning carbon and ecological footprints.

2.2.2 Relationship between green innovation and ED

Green innovation has received much attention in the previous two decades because of its ability to deal with environmental issues. Green innovation is defined as a novel approach to production and process that has the potential to reduce environmental impact

significantly (Wen et al., 2021). Green innovation benefits the environment by reducing environmental harm, lowering costs, and developing new environmentally friendly technologies (Ekins and Zenghelis, 2021). Most studies reveal that green innovation reduces carbon emissions and contributes to ecological footprint reduction. Carrión-Flores and Innes (2010) employed the generalised method of moments (GMM) approach in panel data for 127 manufacturing industries in the USA from 1989 to 2004 to analyse the relationship between environmental innovation (measured by green patent applications) and harmful air pollution. They conclude that environmental innovation helps to reduce poisonous emissions in the USA. This conclusion has been validated by several subsequent research. For example, Lee and Min (2015) studied the impact of green innovation research and development (R&D) spending on carbon emissions and financial performance using a sample of Japanese manufacturing sectors from 2001 to 2010. The research revealed a negative relationship between green R&D and carbon emissions and a positive relationship between green R&D and financial success. Khattak et al. (2020) used the EKC hypothesis to study the complicated relationship between green innovation and CO₂ emissions in BRICS nations from 1980 to 2016. Green innovation efforts in China, India, Russia, and South Africa were shown to have a negative impact on CO₂ emissions but had a positive influence on CO₂ emissions in Brazil. Anwar et al. (2022a, 2023) show that technological innovation improves environmental quality by reducing CO₂ emissions in the case of the seven emerging E-7 (Brazil, China, India, Indonesia, Mexico, Russia, and Turkey) economies.

In the context of Organization for Economic Co-operation and Development (OECD) countries, Ahmed (2020) found a negative impact of green innovation on carbon emissions, and Chu (2022) found a negative impact of green innovation on ecological footprint. The study by Wen et al. (2021) shows that green innovation improves the environmental qualities in South Asian countries. Qin et al. (2021) examined the G-7 (Canada, France, Germany, Italy, Japan, the UK, and the USA) economies' carbon neutrality targets from 1990 to 2019. Their study found that green innovation and renewable energy R&D significantly reduce carbon emissions. Mongo et al. (2021) also found that environmental innovation helps to lower CO₂ emissions in 15 European countries.

Razzaq et al. (2021) show that both consumption- and terrestrial-based carbon emissions-mitigating effect of green innovation is only pronounced at higher emissions quantiles in BRICS nations. Similarly, Jiang et al. (2022) also find that adopting environmental-related technologies reduces consumption-based carbon emissions in BRICS countries. Sun et al. (2022a) show a significant negative impact of green innovation on carbon emissions in the top 10 polluting nations, confirming the positive impact of green innovation on the environment. Li et al. (2022a) analysed the association between green innovation and environmental sustainability from 1991 to 2019 in India. According to the study, an increase in green innovation decreases CO₂ emissions. Zhang et al. (2022) investigate the nonlinear relationship between green investment, economic development, natural resources, green innovation, and China's ecological footprint. Observing the expanding trend of ecological footprints in China, the study aimed to promote green development to prevent ED. Their findings indicated that China should pursue policies that promote green development and innovation in the country, as it helps to improve the environmental qualities by reducing the ecological footprint.

Liu et al. (2022a) explored the asymmetric linkages between environmental innovation and transport emissions for 1990Q1–2018Q4 in India. Their quantile

autoregressive distributed lag approach (QARDL) model shows that environmental innovation lowers transport carbon emissions from the 60th to the 95th quantiles. Ali et al. (2022) also found a significant negative impact of green innovations on CO₂ emissions in the context of BRICS using the augmented mean group (AMG) estimation technique. Lisha et al. (2023) investigated the relationship between green innovation, financial development, natural resources, and environmental sustainability in the case of BRICS nations from 2000 to 2019. Their results show that green innovation significantly reduces carbon emissions. Hence, the study suggests the following hypothesis,

Hypothesis 2 Green innovation has a significant negative impact on carbon and ecological footprint.

2.2.3 Relationship between renewable energy consumption and ED

The ED caused by non-renewable energy encouraged world economies to adopt renewable energy sources for economic growth that did not harm the environment. Renewable energy sources effectively contribute to environmental sustainability by lowering CO₂ emissions and ecological footprint (Iqbal et al., 2022; Radmehr et al., 2022). Several studies have examined the relationships between energy use and ED, but relatively few have explored the significance of renewable energy in environmental sustainability. For instance, Alvarez-Herranz et al. (2017) investigated the effects of renewable energy and energy innovations on environmental quality in OECD countries by taking yearly data from 1990 to 2012. They discovered that renewable energy helps attain sustainability. Kusumadewi et al. (2017) revealed that biomass, solar, and wind energy technologies contribute to reducing pollution. The study of Altıntaş and Kassouri (2020) from 1985 to 2016 found that investments in cleaner energy help to reduce environmental footprints.

Mongo et al. (2021) showed a negative impact of renewable energy consumption on CO₂ emissions in European countries from 1991 to 2014. In the context of the top 10 polluting nations, Sun et al. (2022a) showed a significant negative impact of renewable energy on carbon emissions. In another study, Sun et al. (2022b) found that renewable energy helps improve environmental quality by reducing the ecological footprint in G-11 (El Salvador, Croatia, Georgia, Indonesia, Honduras, Jordan, Pakistan, Morocco, Sri Lanka, and Paraguay) countries. Radmehr et al. (2022) in G-7 countries and Wang et al. (2022) in Next-11 countries discovered a negative association between renewable energy consumption and ecological footprint. The study by Akadiri and Adebayo (2022) found that positive shocks in renewable and non-renewable energy consumption decrease and increase CO₂ emissions in India, respectively. In the case of BRICS countries, the study by Danish et al. (2019) and Khan et al. (2022) demonstrated that renewable energy helps to lessen CO₂ emissions. Again, Danish et al. (2020) revealed a negative impact of renewable energy consumption on the ecological footprint in BRICS countries which further helps to improve the environmental qualities.

Further, Anwar and Malik (2022) in the case of G-7 from 1996-2018, Anwar et al. (2022b) in the case of 15 selected Asian countries from 1990–2014, and Anwar et al. (2023) in the case of E-7 countries from 1996–2020 report the vital role of renewable energy in mitigating CO₂ emission. Similar results were obtained by Cai et al. (2022) in the case of South Asian countries by using the panel FMOLS regression technique. In another study, the result of the feasible generalised least squares (FGLS) estimation

technique by Liu et al. (2022b) shows that a 1% increase in renewable energy consumption mitigates CO₂ emission by 0.144% in E-7 countries. The study by Li and Haneklaus (2022) observed that clean energy consumption helped decrease CO₂ emission by 0.08%–0.14%, whereas coal consumption raised it by 0.75%–0.78% in the long run in India. Hence, the third hypothesis of the study is,

Hypothesis 3 Renewable energy consumption has a significant negative impact on carbon and ecological footprint.

Further, in line with several other studies, the present study uses several control variables like urbanisation, industrialisation, financial development, natural resources, and trade openness in the econometric model to validate the EKC hypothesis (Anwar et al., 2022b; Arzova and Sahin, 2023; Li and Haneklaus, 2022; Mehmood, 2022; Roson and van der Mensbrugghe, 2012; Sahoo and Sethi, 2022; Shah et al., 2022; Sharmin and Tareque, 2018; 2020; Zhang et al., 2022). Hence, all these factors are considered important determinants of ED.

3 Methodology

3.1 Data

The study uses an annual dataset from 1995 to 2018 in BRICS countries. Carbon and ecological footprint variables are used to measure ED. Because these two are more adequate proxies for an environment representing a country's biological and ecological potential (Chaudhry et al., 2022). The main explanatory variables are green innovation, renewable energy consumption, and economic growth. Green innovation shows the total number of fractional count of patents on environmental-related technologies based on the residence of the inventor(s). The GDP and its square term (GDP²) are used to verify the EKC hypothesis. Besides this, other control variables affecting ED are also used, including urbanisation, natural resources, industrial output, industrial productivity, trade openness, and financial development. The financial development index contains the ranking based on the country's financial markets and institutions according to their efficiency, depth, and access (Svirydzenka, 2016). Table 1 depicts each variable's name, its measurement, and sources.

3.2 Model specification

In line with the previous recent literature on the determinants of ED, the study develops an empirical model that takes the following functional form:

$$ED = f(GI, REC, GDP, GDP^2, UR, NR, IND1, IND2, TO, FD) \quad (1)$$

The study used carbon and ecological footprint indicators to capture ED. Thus, the empirical form of the two models is as follows:

$$\begin{aligned} \text{Model 1: } CF_{it} = & \alpha_0 + \alpha_1 GI_{it} + \alpha_2 REC_{it} + \alpha_3 GDP_{it} + \alpha_4 GDP_{it}^2 + \alpha_5 UR_{it} \\ & + \alpha_6 NR_{it} + \alpha_7 IND_{it} + \alpha_8 IND2_{it} + \alpha_9 TO_{it} + \alpha_{10} FD_{it} + \varepsilon_{it} \end{aligned} \quad (2)$$

$$\text{Model 2: } EF_{it} = \beta_0 + \beta_1 GI_{it} + \beta_2 REC_{it} + \beta_3 GDP_{it} + \beta_4 GDP_{it}^2 + \beta_5 UR_{it} + \beta_6 NR_{it} + \beta_7 IND_{it} + \beta_8 IND2_{it} + \beta_9 TO_{it} + \beta_{10} FD_{it} + \varepsilon_{it} \quad (3)$$

Here, i denotes the sample countries, t represents the study period, and ε is the error term. The symbols for the variables are mentioned in Table 1. The study constitutes five countries and 24 periods.

Table 1 Variables, measurements, and sources

<i>Symbol</i>	<i>Variables</i>	<i>Measurement</i>	<i>Sources</i>
CF	Carbon footprint	Global hectares per capita	GFN (2021)
EF	Ecological footprint	Global hectares per capita	GFN (2021)
GI	Green innovation	Natural log of environmental-related technologies (number of patents)	OECD (2023)
REC	Renewable energy consumption	Renewable energy use (% of total energy use)	WDI (2021)
GDP	GDP per capita (proxy for economic growth)	Constant 2015 US\$	WDI (2021)
GDP ²	GDP per capita square	Constant 2015 US\$	WDI (2021)
UR	Urbanisation	Urban population (% of the total population)	WDI (2021)
NR	Natural resources	Total natural resource rent (% GDP)	WDI (2021)
IND1	Industrial output	Industry, value added (% of GDP)	WDI (2021)
IND2	Industrial productivity	Industry, value added per worker (constant 2015 US\$)	WDI (2021)
TO	Trade openness	Trade (% of GDP)	WDI (2021)
FD	Financial development	Comprising sub-indices of the financial institutional index and financial market index	IMF (2020)

Notes: GFN = global footprint network, OECD = Organization for Economic Co-operation and Development, WDI = World Development Indicators, IMF= International Monetary Fund. Global hectare is a biologically productive hectare of land or water body based on the world's average biological productivity for a given year (GFN, 2021; Borucke et al., 2013).

3.3 Techniques employed

The study applied a series of econometrics techniques to achieve the research objectives. First, a cross-sectional independence test was performed to see whether the error terms were cross-sectionally dependent. Next, the study conducted the unit-root test of all variables to check the stationarity. The cointegration test was then performed to check whether the long-run relation exists in the model. Subsequently, the Driscoll-Kraay standard regression technique was employed to estimate the long-term coefficient to solve panel data heterogeneity and cross-dependency concerns.

3.3.1 Cross-sectional dependence test

This study employed one of the sophisticated econometric procedures known as the cross-sectional dependence test (CSD test) introduced by Pesaran (2004) to solve the CSD difficulties between the variables. This test helps address unobserved shock issues before estimating the unit root test and cointegration analysis to avoid biased or misleading results. The CSD test statistic is computed as follows:

$$CSD = \sqrt{\frac{2T}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \widehat{p}_{ij}} \quad (4)$$

where N stands for sample size, T stands for time, and p_{ij} stands for sample estimate of cross-sectional correlation of errors between i and j .

3.3.2 Unit root test

After obtaining the cross-section dependency test, the study looked for the unit root or stationarity in the chosen panel. When dealing with data containing cross-sections and time series, the data must remain stationary. In this regard, the study employed the panel unit root test, such as cross-sectional augmented Dickey-Fuller (CADF) proposed by Pesaran (2007), to address the heterogeneous panel issue while overcoming the cross-section dependence issue between the units. In addition to the CADF test, the study performed the Levin-Lin-Chu unit-root test (Levin et al., 2002). Both tests were performed under the null hypothesis of non-stationarity or the presence of the respective variable's unit root against the alternative stationarity hypothesis.

3.3.3 Cointegration test

The study used the Westerlund (2007) error correction model (ECM) to detect cointegration among heterogeneous variables after testing stationarity or the unit root. Westerlund (2007) addresses the issue of heterogeneous slope parameters and solves the cross-section dependency problem. In addition, the study used the Kao residual cointegration test (Kao, 1999) to determine the long-run relationship between variables. Cointegrating relationships are required before employing proper regression methods to generate long-run estimates.

3.3.4 Regression analysis

CSD causes incorrect estimations in simultaneous equation models. The study employed the fixed effect with Driscoll-Kraay standard errors technique to overcome heterogeneity CSD issues on panel data and auto-correlation (Driscoll and Kraay, 1998). This approach may be used to compensate for missing values and can be used for both balanced and unbalanced data (Hashemizadeh et al., 2021). When dealing with stationarity difficulties and cross-sectional dependencies, it has given reliable and persistent findings of similarity in prior research (Danish and Ulucak, 2020; Hashemizadeh et al., 2021; Wang et al., 2021). The study is also suitable for a long period with a small cross-section. The test was performed in the State 17.0 software using the command given by Hoechle (2007).

4 Empirical findings and discussion

The study will present the estimated results, interpretation, and discussion in this section. Table 2 provides the results of Pesaran's (2004) cross-section dependence test. From Table 2, we can see that the results of the CSD-test of all variables are significant at a 1% level. That means the study rejected the null hypothesis of no cross-sectional dependency and accepted the alternative hypothesis. So, all variables/countries are cross-sectionally dependent upon each other, which verifies that disturbance in one country will affect other countries. Also, we can see that most of the value of correlation and absolute correlation of the residuals in each variable is more than 0.5, which is very high. So, there is enough evidence for the presence of cross-section dependence.

Table 2 Results of the CSD test

<i>Variables</i>	<i>CSD-test</i>	<i>Corr</i>	<i>Abs (corr)</i>
CF	10.510 ^a	0.678	0.678
EF	5.440 ^a	0.351	0.52
GI	10.540 ^a	0.68	0.68
REC	6.390 ^a	0.413	0.573
GDP	14.320 ^a	0.924	0.924
GDP ²	13.650 ^a	0.881	0.881
UR	14.810 ^a	0.956	0.956
NR	10.540 ^a	0.681	0.681
IND1	6.600 ^a	0.426	0.486
IND2	9.520 ^a	0.614	0.614
TO	4.050 ^a	0.261	0.461
FD	10.690 ^a	0.69	0.69

Notes: Level of significance at the ^a = 1%. Corr = average pairwise correlation of the residual and Abs (corr) = absolute average pairwise correlation of the residuals.

Table 3 provides the unit root test results conducted using the CADF test by Pesaran (2007) and the Levin-Lin-Chu unit-root test by Levin et al. (2002). Both these techniques are used over the data at levels I(0) and the first difference I(1). The table shows that all variables are significant at 1% at the first difference except GDP, GDP², UR, and IND2 using the CADF test. Except for UR, all variables are significant at 1% at the first difference using the Levin-Lin-Chu unit-root test. This rejects the null hypothesis of the presence of unit root and accepts the alternative hypothesis of stationarity of all variables. So, we need to proceed further with the cointegration test.

Table 4 provides the results of the empirical estimation of the cointegration test conducted using Westerlund (2007) and Kao's (1999) residual cointegration test. The value from the table clearly shows that both the models are significant at 1% and 5% of all parameters using the Kao test for cointegration. Whereas, using Westerlund's (2007) techniques, only one parameter is significant at the 5% level. As a result, the null hypothesis that no cointegration existed among the variables was rejected. Instead, the occurrence of long-run cointegration might be considered as an alternative hypothesis.

Table 3 Results of unit-root test

<i>Variables</i>	<i>CADF test statistics</i>		<i>Levin-Lin-Chu unit-root test</i>	
	<i>Level (t-bar)</i>	<i>First difference (t-bar)</i>	<i>Level (adjusted t)</i>	<i>First difference (adjusted t)</i>
CF	-1.476	-2.936 ^a	-0.8190	-5.0310 ^a
EF	-1.642	-3.734 ^a	-1.3488 ^c	-6.0809 ^a
GI	-4.111 ^a	-5.291 ^a	-0.5493	-8.7481 ^a
REC	-2.057	-4.145 ^a	-0.1046	-4.3813 ^a
GDP	-0.496	-1.704	-0.7387	-3.8436 ^a
GDP ²	0.988	-0.502	4.7770	-3.0794 ^a
UR	-1.099	1.008	-1.8554	-1.2767
NR	-1.762	-4.126 ^a	-1.9205 ^b	-7.8040 ^a
IND1	-1.383	-3.731 ^a	0.3449	-3.3614 ^a
IND2	-0.518	-3.062	0.1874	-5.8676 ^a
TO	-1.549	-2.932 ^a	-1.2556	-6.0000 ^a
FD	-2.059	-5.217 ^a	-1.5890 ^c	-9.3635 ^a

Note: Level of significance at the ^a = 1%, ^b = 5%, and ^c = 10%.

Table 4 Results of the panel cointegration test

<i>Kao test for cointegration</i>	<i>Model-1</i>		<i>Model-2</i>	
	<i>Statistics</i>	<i>p-value</i>	<i>Statistics</i>	<i>p-value</i>
Modified Dickey-Fuller t	-3.268 ^a	0.0005	-7.1612 ^a	0.000
Dickey-Fuller t	-2.3198 ^b	0.0102	-4.4645 ^a	0.000
Augmented Dickey-Fuller t	-2.8839 ^a	0.002	-5.1744 ^a	0.000
Unadjusted modified Dickey-Fuller	-2.8802 ^a	0.002	-6.9648 ^a	0.000
Unadjusted Dickey-Fuller t	-2.2126 ^a	0.0135	-4.4385 ^a	0.000
<i>Westerlund ECM panel cointegration test</i>	<i>Model-1</i>		<i>Model-2</i>	
	<i>Value</i>	<i>p-value</i>	<i>Value</i>	<i>p-value</i>
Gt	-2.339	0.217	-1.944	0.53
Ga	-4.818	0.944	-5.705	0.905
Pt	-6.366 ^b	0.015	-5.919 ^b	0.035
Pa	-7.216	0.368	-8.221	0.26

Note: Level of significance at the ^a = 1% and ^b = 5%.

Table 5 shows the results of the Driscoll-Kraay standard error estimates, where the dependent variables are carbon footprint and ecological footprint in models 1 and 2, respectively. Our study's main explanatory variables are green innovation and renewable energy consumption. The table shows that GDP is positively related to both carbon and ecological footprint, and GDP² is negatively related to carbon and ecological footprint. The results are also highly significant in both models. Thus, the study validated the inverted U-shaped EKC hypothesis in both carbon and ecological footprint cases in BRICS nations and confirmed Hypothesis 1. Khan et al. (2022) and Karthikeyan and

Murugesan (2022) also validated the EKC hypothesis in the case of BRICS nations by considering CO₂ emissions as an indicator of ED. The EKC hypothesis signifies that as GDP increases, the quality of the environment deteriorates because governments have a casual attitude toward it and desire more incredible growth to enhance their per capita income. After a significant increase in per capita income, people seek a better environment, including fresh air and clean water (Farooq et al., 2021). In this stage, environmentally friendly energy infrastructures may be reinforced and changed towards clean and green energies. Furthermore, firms' and governments' financing capacity is improved; as a result, environmental quality will improve as economic growth increases (Esmacili et al., 2023). Thus, the current study's findings support the existence of the EKC hypothesis, like the study of Ganda (2018), Dogan et al. (2019), Gopakumar et al. (2022), Gupta et al. (2022), Harrathi and Almohaimeed (2022), Cai et al. (2022), Liu et al. (2022a), Farooq et al. (2021) and Esmacili et al. (2023).

The empirical results also showed that green innovation has a significant negative impact on both inclusive ED measures, namely, carbon and ecological footprint, at a 1% significance level. More specifically, a 1% increase in green innovation leads to a 0.229% reduction in carbon footprint and a 0.226% reduction in ecological footprint. Hence, it confirms Hypothesis 2. Similar results were obtained by Liu et al. (2022a) in the case of India by taking transport carbon emissions as a measurement of ED. The results are also consistent with the finding of Mongo et al. (2021) from 15 European countries, Qin et al. (2021) from G-7 countries, Zhang et al. (2022) from China, and Li et al. (2022a) from highly polluted Asian countries. In the context of BRICS also, similar results obtained by Khattak et al. (2020), Razzaq et al. (2021), Jiang et al. (2022), Ali et al. (2022) and Lisha et al. (2023) by using different proxies of ED. Thus, the present study confirms that green innovation is important in reducing ED in BRICS.

Moving on to the influence of renewable energy on ED, the results demonstrate that the renewable energy coefficient is significant and negative considering both carbon and ecological footprints. So, Hypothesis 3 is validated. As a 1% increase, renewable energy reduces the carbon and ecological footprint by 0.024% and 0.032%, respectively. This demonstrates how renewable energy plays an integral part in lowering the footprint. The negative value of the renewable energy coefficient indicates that the BRICS economies are converting to green energy by substituting fossil-fuel energy (Liu et al., 2022b). This also suggests that the BRICS countries are on the right track toward achieving SDGs by incorporating and advancing renewable energy technology (Danish et al., 2020). The result is consistent with Danish et al. (2019 and 2020) and Khan et al. (2022) in BRICS, Liu et al. (2022b) and Anwar et al. (2022a, 2023) in E-7 countries, Cai et al. (2022) in South Asian economies, Anwar et al. (2022b) in Asian countries, Esmacili et al. (2023) in Next-11 countries, who stated that the use of renewable energy improves the environmental qualities.

Urbanisation has a significant positive impact on carbon footprint and ecological footprint. This signifies that as urbanisation goes on, it deteriorates the environment more. A 1% increase in urbanisation raises the carbon and ecological footprints by 0.06% and 0.03%, respectively. This result is similar to the finding of Sharmin and Tareque (2018), Anwar et al. (2022b), Farooq et al. (2021), Cai et al. (2022), Li and Haneklaus (2022) and Gupta et al. (2022). This finding indicates that BRICS's environmental quality has deteriorated dramatically as a result of the recent growth in urbanisation. Due to urbanisation, people's lifestyles improve in terms of easy transportation from one location to another, greater work prospects, more income, and so on. This increases the

need for durable products and the widespread usage of electrical gadgets for fast services. Hence, urbanisation significantly influences ecological conditions due to deforestation, water contamination, climate change, and a population increase in metropolitan areas (Gupta et al., 2022).

In the case of using natural resources, it has a significant positive impact on the ecological footprint. But it found an insignificant impact on carbon footprint. Because ecological footprint includes five other types of components (cropland, grazing land, fishing grounds, built-up land, and forest area) except carbon footprint, which is directly affected by the use of natural resources (Lin et al., 2018). A 1% increase in natural resources leads to a 0.014% rise in ecological footprint. This result is in line with Mehmood (2022), Nathaniel et al. (2021), Zhang et al. (2022) and Sun et al. (2022b), who argued that the extraction of natural resources raises the ecological footprint. Thus, it suggests the BRICS nations use natural resources efficiently.

Table 5 Results of fixed effect model with Driscoll-Kraay standard errors

<i>Variables</i>	<i>Model: 1 (CF)</i>		<i>Model-2 (EF)</i>	
	<i>Coefficient</i>	<i>t-statistics</i>	<i>Coefficient</i>	<i>t-statistics</i>
GI	-0.229a	-6.06	-0.226a	-5.64
REC	-0.024a	-4.7	-0.032a	-6.16
GDP	0.00047a	4.39	0.000568a	4.48
GDP ²	-1.31E-08 ^b	-2.1	-1.94E-08 ^a	-2.86
UR	0.06 ^a	3.92	0.03 ^c	1.94
NR	0.0056	0.98	0.014 ^b	2.25
IND1	0.021b	2.76	0.023 ^a	2.91
IND2	-7.5E-05 ^a	-4.94	-3.66E-05 ^b	-2.59
TO	-3.8E-05	-0.01	-0.005	-1.59
FD	-0.197	-0.75	-0.528	-1.56
Constant	-1.569 ^b	-2.38	1.049	1.61
F-statistics	706.61		353.98	
Prob. F-statistics	0.000		0.000	
R-squared	0.875		0.875	

Note: Level of significance at the ^a = 1%, ^b = 5%, and ^c = 10%.

Industrial output is a significant positive contributor to carbon and ecological footprint, whereas industrial productivity is a negative contributor. A 1% increase in industrial output raises the carbon and ecological footprints by 0.021% and 0.023%, respectively. BRICS nations are now in the developing stage, so their industrialisation rate is mostly too high, which negatively impacts the environment. The results align with the study of Sharmin and Tareque (2018) and Sahoo and Sethi (2022).

Lastly, the study found a positive but insignificant impact of trade openness and financial development on both carbon and ecological footprints, but the impact is insignificant. The insignificant positive impact of trade openness on ED aligns with the result of Shah et al. (2022). Studies that found a positive impact of financial development on ED include Anwar et al. (2022b), Farooq et al. (2021) and Arzova and Sahin (2023).

To check the robustness of the results, the study used the FMOLS technique developed by Phillips and Hansen (1990). The results of the test are presented in Table 6. From the robustness analysis, it is evident that green innovation and renewable energy consumption significantly negatively impact both indicators of ED. Further, an inverted U-shaped EKC was confirmed only in the case of ecological footprint. Also, the signs on the coefficients of control variables are in line with those in Table 5.

Table 6 Robustness check

<i>Variables</i>	<i>Model: 1 (CF)</i>		<i>Model: 2 (EF)</i>	
	<i>Coefficient</i>	<i>t-statistics</i>	<i>Coefficient</i>	<i>t-statistics</i>
GI	-0.263 ^a	-6.583	-0.263 ^a	-6.452
REC	-0.024 ^b	-2.349	-0.034 ^a	-3.243
GDP	0.00047 ^a	2.737	0.0005634 ^a	3.073
GDP ²	-1.23E-08	-1.128	-1.73E-08 ^c	-1.763
UR	0.065 ^a	4.450	0.035 ^b	2.36
NR	0.005	0.478	0.013	1.190
IND1	0.022 ^c	1.763	0.027 ^b	2.096
IND2	-7.84E-05 ^a	-3.176	-3.53E-05	-1.401
TO	-0.001	-0.283	-0.004	-0.958
FD	-0.090	-0.130	-0.350	-0.496
R-squared	0.987		0.989	
Adjusted R-squared	0.985		0.987	

Note: Level of significance at the ^a = 1%, ^b = 5%, and ^c = 10%.

5 Conclusions and policy implications

Renewable energy and green innovation are major solutions for combating ED problems. Despite their importance, only a few empirical investigations have examined how these two factors affect carbon and ecological footprints. Hence, the study investigated the impact of green innovation and renewable energy consumption on carbon footprint and ecological footprint in BRICS countries from 1995 to 2018 in the EKC framework. A series of econometric techniques and the Driscoll-Kraay standard error regression technique were used to achieve the research objectives. The result of Driscoll-Kraay standard errors shows that green innovation and renewable energy consumption help mitigate ED by reducing the carbon and ecological footprint in the BRICS countries. The study validated the inverted U-shaped EKC hypothesis in the determinants of ED: carbon footprint and ecological footprint.

Further, the empirical results found a negative association between industrial productivity and ED. In contrast, urbanisation and industrial output are raising both types of footprints. However, trade openness and financial development are not playing any role in ED or sustainability when the more inclusive measures of ED in terms of carbon and ecological footprint are considered. Further, the robustness test was also conducted using the FMOLS regression technique, which gave similar results.

As a policy implication, the study's findings suggest that the BRICS countries should invest more in new techniques associated with green innovations, which will be further helpful for promoting environmental sustainability. Further, the government should encourage using renewable energy, as it is non-polluting and inexpensive, making it ideal for reducing reliance on traditional fossil fuels to enhance environmental quality (Liu et al., 2022b). Governments of BRICS nations should make it easier for the private sector to establish green energy projects (such as wind, solar, and bioenergy) and give subsidies to consumers and businesses for implementing renewable energy solutions.

Policymakers must facilitate the adoption of renewable energy technology by investing in R&D, and the need to enhance manufacturing standards and disseminate relevant ecologically friendly technology must be prioritised (Shobande et al., 2023). To minimise carbon footprint, policymakers must develop strategies that allow businesses to boost diversity and inclusion, invest in energy efficiency, minimise waste, and encourage recycling. Policymakers must give policy and program support for renewable energy expansion and adopt sustainable business practices. By using renewable energy and promoting green innovation, it is possible to reduce the household's ecological footprint too.

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