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After the Johannesburg II Declaration, What Next for Ecological Sustainability in BRICS? Perspectives on Green Innovations and Green Transitions

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Received: 23 March 2024 | **Revised:** 11 December 2024 | **Accepted:** 23 December 2024

Keywords: BRICS | ecological sustainability | green technology | green transition | load capacity factor

ABSTRACT

Advancing ecological sustainability, a major focus of the SDGs, necessitates evaluating the influence of green energy, sustainable technology, and resource utilization on ecological load capacity factors—an area that has remained underexplored in existing research. Also, the LCF method, which elucidates the unique features of the supply and demand dynamics in the natural environment, is still not used by BRICS environmental modelers. This study examined panel data of pertinent LCF predictors spanning from 1980 to 2021. The analysis utilized several advanced methodologies, and a new viewpoint was presented through the application of the panel-frequency domain Granger causality test. The results demonstrate that (i) green transitions notably enhance LCF across various quantile distributions, and (ii) green technologies exert a moderately positive influence on LCF. The analysis suggests that ongoing shifts towards clean energy and the encouragement of eco-friendly technological innovations necessitate well-planned policies to enhance LCF within the BRICS nations.

1 | Introduction

The BRICS nations are frequently praised for their tangible commitments to environmental sustainability. However, a critical examination of their environmental strategies reveals several areas of concern. Firstly, while these countries are indeed prominent global consumers of natural resources and energy (Adebayo and Samour 2023; Alam, Destek, and Haque 2024), their sustainability commitments often lack the comprehensive action plans necessary to address the scale of their environmental impact. The ongoing evaluation of factors impacting ecological sustainability is undeniably important. However, the empirical studies conducted so far appear inadequate in addressing the persistent environmental challenges these nations face. Secondly, the 15th BRICS summit held in Johannesburg reiterated the importance of sustainable development. While these goals are commendable, the summit's lack of specific, measurable targets raises questions about its practical impact. Thirdly, the reiterated commitment to the UN SDGs and alignment with the UN framework on climate change and the Paris Agreement are positive signals. However, the absence of detailed implementation strategies casts doubts on the sincerity and effectiveness of these commitments. Fourthly, the BRICS Green Fund initiative, although a step in the right direction, also warrants scrutiny. While it aims to support projects and policies fostering green energy and technology, the initiative's scope and funding mechanisms remain vague. Without clear guidelines and substantial financial backing, the Green Fund risks being more symbolic than transformative.

The environmental issues confronting the BRICS nations are considerable: China, Russia, India, and Brazil are listed among the top 10 worldwide emitters, with South Africa positioned 17th. This striking statistic underscores the significant environmental challenges confronting these nations, which are also among the 20

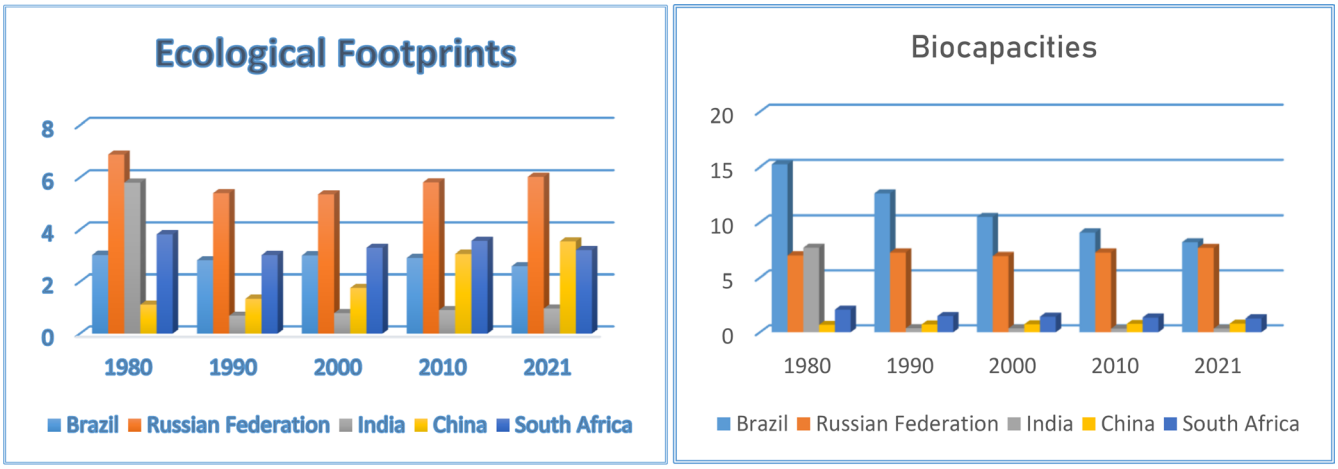
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largest global economies by gross domestic product (GDP). This economic strength is intricately associated with their reliance on conventional energy sources, including coal, oil, and natural gas (Alam, Destek, and Haque 2024). This connection, while correct, neglects the complexity associated with the transition to renewable energy in quickly emerging economies, including socio-economic and political obstacles that may impede such transitions. Moreover, the reality that almost one-third of the global population resides in these nations (Adebayo and Samour 2023) underscores the significant impact that environmental policies in BRICS countries can have on global sustainability initiatives. This emphasizes the critical necessity for well-structured policies to advance sustainable development in these nations. A thorough examination of the political will and institutional capability necessary for implementing these reforms will facilitate a more complete understanding of the routes to sustainability in the BRICS nations. This study is essential for formulating effective strategies to tackle environmental concerns in these vital locations.

While BRICS nations contribute to approximately 40% of global green energy investments and utilization (Alam, Destek, and Haque 2024), their environmental performance remains concerning. Despite their significant role in green energy, most BRICS countries continue to underperform in environmental sustainability. Figure 1a,b visually illustrates this discrepancy, showing the ecological footprints and biocapacities of each country. Brazil and the Russian Federation stand out as exceptions, having successfully maintained biocapacities that exceed their ecological footprints, indicating a more sustainable environmental balance. However, the environmental outlook for China, India, and South Africa is troubling, as these nations face disproportionately large ecological footprints relative to their limited biocapacity, highlighting a severe imbalance and raising questions about their long-term environmental sustainability.

With Brazil and the Russian Federation as notable outliers, the Global Footprint Network (GFN 2024) exposes major biocapacity deficits across most BRICS countries. While China, India, and South Africa have significant biocapacity deficits with numbers of 340%, 200%, and 180%, respectively, Brazil and Russia show biocapacity reserves of 219% and 30%, respectively. The balance between a nation's biocapacity and its



a b

FIGURE 1 | (a) Ecological Footprints of BRICS countries—1980–2021. (b) Biocapacity scores of BRICS countries—1980–2021.

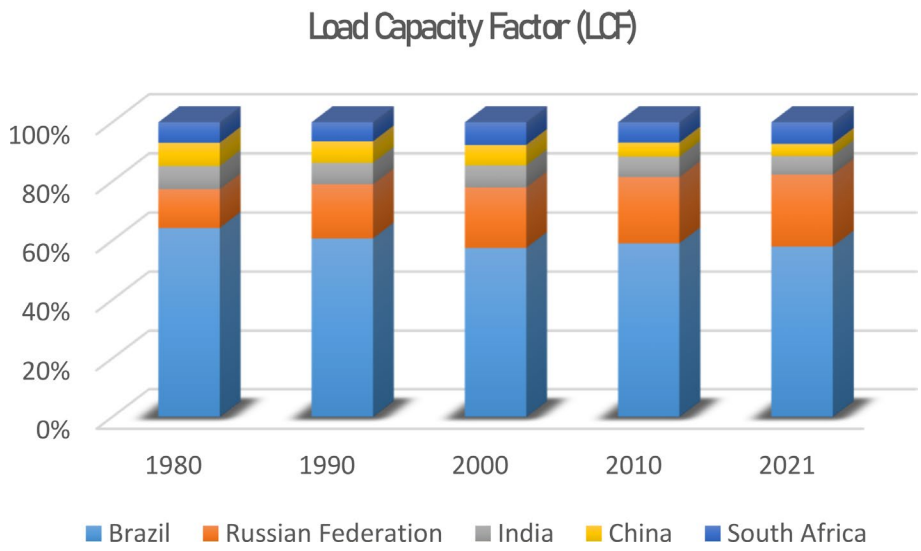


FIGURE 2 | Load Capacity Factors of BRICS countries—1980–2021.

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environmental impact is known as its reserve/deficiency. A nation with a biocapacity surplus exceeds its ecological footprint; a deficit denotes a shortage. Most BRICS countries are failing on their pledges to reach important sustainable development goals (SDGs), especially objectives 7, 11, and 13. This highlights a concerning trend.

Figure 2 provides insights into the environmental performance of BRICS nations using the Load Capacity Factor (LCF), a metric for environmental sustainability. The LCF is designed to account for both the demand and supply aspects of the natural environment (Adebayo and Samour 2023; Nwani et al. 2024; Uche and Ngepah 2024) and to illustrate the environment's capacity to regenerate despite adverse human activities (Pata et al. 2023). Mathematically, LCF is computed as a ratio of biocapacity to ecological footprint, an LCF score around 1 indicates ecological balance, whereas scores significantly below 1 suggest ecological imbalances (Siche et al. 2010). Additionally, Figure 2 reveals that most BRICS countries exhibit poor ecological performance, with China, India, and South Africa scoring below the sustainability threshold for ecological factors. In contrast, Brazil, and to a lesser extent Russia, surpass this threshold. Brazil's ecological load capacity factor is particularly notable, indicating the implementation of effective policy frameworks that differentiate it from the other BRICS nations. Figure 1 further supports this observation, showing Brazil's consistently low ecological footprints over the years. However, Brazil's biocapacity has significantly declined recently, while Russia's has improved. These findings highlight the urgent need for comprehensive empirical evaluations that consider both primary and secondary factors in these ecological scenarios.

The current ecological imbalances in BRICS countries, particularly India, China, and South Africa, necessitate immediate empirical evaluations to identify the primary contributing factors. Policymakers are significantly concerned about these imbalances and are seeking essential measures to mitigate their adverse trends. However, previous research (Awosusi et al. 2022; Adebayo and Samour 2023; Alam, Destek, and Haque 2024; Ullah et al. 2023) has several critical shortcomings. Firstly, these studies have not utilized new datasets or novel panel estimators, which are crucial for obtaining more accurate and current insights. Secondly, they have overlooked the significant impacts of green technological developments and transitions. This omission is particularly problematic as green technology and transitions play a vital role in ecological resilience. Previous studies have overlooked the impact of resource use and urbanization as predictors of ecological imbalances, resulting in incomplete analyses. Furthermore, some recent studies (Alam, Destek, and Haque 2024; Jiang et al. 2023; Li et al. 2023) that focus on the BRICS nations have measured environmental quality using metrics other than ecological load capacity. This approach may not accurately capture the current economic realities, leading to potentially misleading conclusions. Given these deficiencies, it is clear that earlier investigations may provide an incomplete and possibly misleading picture. Therefore, comprehensive empirical evaluations that incorporate new datasets and novel methodologies, while considering the roles of green technology, resource use, and urbanization, are urgently needed to effectively address the ecological imbalances in BRICS countries.

This research addresses a significant gap in the past studies by investigating the BRICS nations from several fresh perspectives. First, it provides the first in-depth analysis of how green technologies and transitions have impacted the load capacity factor in BRICS countries using the latest data from the Global Footprint Network (GFN) following the Johannesburg Declaration II. Second, unlike previous studies, this research incorporates variables such as economic growth, urbanization, and natural resource usage, which have not been considered before. Third, it employs time-variant panel estimators, a methodological enhancement now standard in the field, ensuring more reliable empirical estimates and their relevance for policy adjustments. Lastly, this study introduces a novel approach by applying panel frequency-domain Granger causality, a method not previously used in this context. As a result, policymakers in the BRICS nations can use these empirical findings to guide policy changes in response to human-induced factors affecting environmental quality. Additionally, the insights gained from this study may be beneficial for other developing and emerging economies facing similar environmental challenges.

The rest of the study: (ii) literature, (iii) methodology, (iv) analysis and discussions (v) conclusion and policy option.

2 | Literature

Two significant theoretical models prevail in the research on ecological sustainability: the Environmental Kuznets Curve (EKC) and the Load Capacity Curve (LCC) hypothesis. Building on Kuznets's seminal research, the former posits an inverted U-shaped correlation between economic growth and environmental harm, indicating that early economic advancement leads to environmental degradation, but after reaching a specific threshold, further development yields environmental enhancements (Hakkak, Altintaş, and Hakkak 2023). It provides a useful framework for investigating the link between environmental quality and economic development; yet, its application is not without limitations. Notably, the hypothesis assumes that environmental improvements are a natural consequence of economic growth, contingent upon factors such as effective policies, technological advancements, and strong institutions, and posits that environmental improvements are a natural consequence of economic growth, contingent upon factors such as effective policies, technological advancements, and strong institutions (Alola, Özkan, and Usman 2023). However, this assumption may overlook the complexities inherent in different economic contexts, for instance, in low-income countries where economic and institutional conditions differ significantly from those in higher-income nations (Hossain et al. 2023; Hossain, Rej, and Hossain 2023). As such, the general applicability of the EKC hypothesis remains questionable, particularly in regions with weaker institutional frameworks or lower levels of technological innovation.

One the other hand, the LCC hypothesis documents the connection between income and load capacity factor, projecting immediate adverse effects followed by long-run beneficial influence. The intuition is that this framework posits a U-shaped relationship: initially, economic affluence leads to environmental degradation, but once a certain income threshold is reached,

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further growth results in environmental improvements (Pata and Kartal 2023). While the LCC hypothesis provides a useful framework for understanding this relationship, its inconsistent validation and varied outcomes across different contexts highlight significant flaws. These challenges emphasize the need to explore the impact of green technological developments and transitions on load capacity factors, particularly in BRICS countries. To clarify these issues, a thematic review of similar prior works is presented.

The empirical literature on the ecological load capacity factor can be categorized into two primary areas: the first examines the correlation between green technological innovations and LCF, while the second explores the relationship between LCF and the green transition. Advancements in green technology have been praised for enhancing LCF, though the evidence remains inconsistent. Studies by Zhao et al. (2023) and Pata and Samour (2022) attempt to provide a comprehensive understanding of the relationship between load capacity and renewable energy. Their findings emphasize the importance of renewable energy; however, they overlook the potential impacts of green technological advancements—a critical oversight given the significant role technology plays in sustainable environmental progress. Addressing this gap, Karimi Alavijeh et al. (2023) investigated the impact of environmental control technologies on CO_2 emissions in EU countries, demonstrating that these innovations contribute to environmental improvements.

Similarly, Uche, Das, and Bera (2023) noted that technological innovation could foster environmental stability in India, though they also highlighted the transient nature of these improvements and suggested the need for more sustainable, long-term solutions. Further studies by Akram et al. (2023), Ibrahim et al. (2023), Jahanger et al. (2023), Jahanger et al. (2023), Han et al. (2024), Radmehr et al. (2023) and Qi, Ibrahim, and Saleh Al-Faryan (2023) found that environmental technological innovations are crucial for enhancing environmental quality, providing a strong argument for adopting advanced technologies in environmental policies. However, Uche et al. (2023) present a counterpoint, noting that in BRICS countries, environmental-control technology sometimes deteriorated environmental health. This contradictory finding underscores the complexity of technological impacts and the necessity for context-specific research.

Research has demonstrated that technological innovations are crucial for preserving environmental quality in developed countries. For instance, Anwar et al. (2023) and Çakar et al. (2022) found that technological innovation significantly enhances environmental quality by reducing carbon emissions in G7 countries. Guan et al. (2023) contended that these beneficial effects are considerably affected by alterations in economic systems, suggesting potential instability in depending exclusively on technology innovation for enduring environmental enhancements. Liu et al. (2022) demonstrated that green innovation enhanced ecological load capacity factor in Brazil and South Africa. Research by Herman and Xiang (2022) and Dogan and Pata (2022) demonstrated that technical innovation improves ecological quality in G7 countries, whereas Ni, Yang, and Razzaq (2022) verified that technological innovation increases the load capacity factor in resource-intensive economies. Saqib, Ozturk, and Usman (2023) emphasized the positive effects of technological advancements on environmental quality in emerging economies. On the contrary, Andrew et al. (2024) present a compelling argument that while technological diffusion reduces CO_2 emissions, it concurrently increases the ecological footprint. This dual effect challenges the presumed overall environmental benefits of technological diffusion. Pata et al. (2023) further complicate the narrative by demonstrating that in Germany, technological innovations not only reduce CO_2 emissions but also lower the load capacity factor, suggesting a potential trade-off between emission reductions and ecological balance. These findings are echoed by Adebayo and Kirikkaleli (2021) and Rout, Gupta, and Sahoo (2022), who found that technological innovations failed to improve the ecological footprints in Japan and BRICS countries, respectively. Such evidence calls into question the efficacy of technological innovations as a standalone solution for environmental improvement. In light of the need for a more comprehensive understanding of these intricate relationships, the present study aims to delve further into this matter by postulating a positive correlation between environmentally friendly technical advancements and the load capacity factor.

Another strand of literature posits that the green transition, characterized by shifting from non-renewable energy to clean energy sources, significantly enhances the ecological LCF, leading to improved environmental quality and sustainable development. Despite ongoing studies, conflicting results persist in this field. Khan et al. (2023) proved that clean energy improves environmental quality in both G7 and E7 nations. However, this assertion is not universally accepted. While several studies have reported similar findings in different contexts—such as Iorember et al. (2021) for South Africa, Dogan and Pata (2022) for G7 countries, Obiakor, Uche, and Das (2022) for West Africa, Liu et al. (2022) for Brazil, and Uche et al. (2022) for E7 countries—these studies fail to provide a definitive understanding of the relationship.

Yang et al. (2023) found that green energy improves the LCF in BRICS nations and the United States. Li et al. (2023) also highlighted the positive effects of renewable energy on LCF. Similarly, Samour et al. (2023), Pata et al. (2023), and Ullah et al. (2023) observed comparable results in their studies of the BRICS, OECD, German, and BRICS-T economies. However, these findings do not resolve the ongoing debate regarding the relationship between LCF and renewable energy. For instance, Pata and Isik (2021) noted a positive impact of renewable energy on LCF in the United States but found no significant effect in Japan. Huilan et al. (2022) reported that renewable energy reduced LCF in Mexico, while Pata and Samour (2022) observed a negative impact in France. Xu et al. (2022) found no improvement in LCF due to renewable energy in the case of Brazil. Further, Pata and Kartal (2023) and Alam, Destek, and Haque (2024) demonstrated that renewable energy decreases LCF in South Korea and negatively affects environmental quality in BRICS nations. These studies highlight significant inconsistencies, indicating that the impact of renewable energy on LCF is not uniformly positive. Therefore, more advanced research is necessary to reconcile these conflicting findings. This study aims to further explore this issue, hypothesizing a positive correlation between green technologies and the load capacity factor.

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2.1 | Literature Gap

This research delves deep into the elements that influence load capacity in BRICS economies, highlighting how green technology has had a significant influence on these growing regions. Moreover, it includes elements such as natural resource exploitation, economic growth, and urban development, which have been neglected in prior research. Moreover, prior studies utilized datasets that failed to consider the post-COVID-19 period, rendering their conclusions possibly incongruous with contemporary economic conditions. This study's application of innovative econometric tools amplifies its contribution, as prior research frequently depended on less flexible methodologies. As a result, their findings were less efficacious in advancing sustainable development. Consequently, additional empirical research is required to clarify the dynamic interactions among these indicated components.

3 | Materials and Methods

This section comprises three sub-components. Accordingly, the components comprise data description and sources, the empirical model, and the relevant estimation techniques.

3.1 | Data Descriptions and Sources

The relevant data consists of annual panel data sets for Brazil, the Russian Federations, India, China, and South Africa (BRICS). Accordingly, the data set stretches for 42 years for each country during 1981–2021 period. However, it is 30 years (1992–2021) for the Russian Federation. It is essential to highlight the limitations imposed by data availability. Meanwhile, unlike prior studies (Adebayo and Samour 2023; Li et al. 2023; Samour et al. 2023; Zhao et al. 2023), the current investigation is based on the most recent data set from the Global Footprint Network (GFN 2024). Accordingly, the most recent update consists of the post-COVID-19 data sets that were unavailable in existing studies. In this respect, the current study took advantage of this recent development to enrich its novelty. In what follows, Table 1 comprehensively describes the peculiarities and sources of the entire data series used in this study.

Notably, the dependent variable—load capacity factor (LCF), is an estimated series. The LCF is the ratio of the biocapacity factor and ecological footprint. This procedure follows the ratification of Siche et al. (2010). Moreover, several studies relied on this estimation protocol to calculate the load capacity factor (Pata et al. 2023; Uche and Ngepah 2024). Notably, the relevant control variables were selected based on insights gained from prior studies. This includes Khan, Hou, and Le (2021), Uche and Effiom (2021), and Uche and Ngepah (2024). Hence, the expected outcomes of the present investigation are novel, all-encompassing, and amenable to policy moderation.

3.2 | Model Specification

Following insights from prior studies (Ni, Yang, and Razzaq 2022; Alola, Özkan, and Usman 2023; Uche and Ngepah 2024), a modified Cobb–Douglas economic framework is adopted in this study.

TABLE 1 | Data description and sources.

Series	Notation	Unit of measurement	Source
Biocapacity factor	*BioCap*	gha per person	GFN
Ecological footprint	*EcoF*	gha per person	GFN
Load capacity factor	*LCF*	Estimated	Author's
Green technology	*GreenTech*	Patent on environmental technology	OECD
Green transition	*GreenTran*	Low-carbon energies	OWID
Resource utilization	*RUtil*	% GDP of natural resource rents	WDI
Economic expansion	*Expan*	GDP per capita—current US$	WDI
Urbanization	*Urban*	Urban population—percentage of the total population	WDI

Note: GFN, OECD, OWID and WDI denote Global Footprint Networks, Organization for Economic Cooperation and Development, Our World in Data, and World Development Indicator, respectively.

Ideally, the framework is adopted to express the dynamic relationships between load capacity factors and sets of predictors. Particularly, the environmental sustainability paths of the BRICS economies are ascertained through the responses of LCF to green technologies and green transitions. Likewise, the influence of the relevant control variables (resource utilization, economic expansions, and urbanization) is explored. Notably, scholars (Akadiri et al. 2022; Ni, Yang, and Razzaq 2022; Opuala, Omoke, and Uche 2023; Pata and Isik 2021) are also divided on their opinions about the effects of these variables on environmental quality. Forthwith, the mathematical protocol of the envisaged relationship is expressed in Equation (1).

$$LCF_{it} = f\left(GreenTech_{it}, GreenTran_{it}, RUtil_{it}, Expan_{it}, Urban_{it}\right) \tag{1}$$

where LCF_{it}, $GreenTech_{it}, GreenTran_{it}, RUtil_{it}, Expan_{it}$, and $Urban_{it}$ depict ecological load capacity factor, green technology, energy transition, resource utilization, economic expansion, and urbanization, respectively. Equation (1) is modified into an econometric scheme and subsequently captured in Equation (2).

$$\begin{aligned} LCF_{it} = {} & \varphi_0 + \varphi_1 GreenTech_{it} + \varphi_2 GreenTran_{it} \\ & + \varphi_3 RUtil_{it} + \varphi_4 Expan_{it} + \varphi_5 Urban_{it} + \varepsilon_{i,t} \end{aligned} \tag{2}$$

where i, t represent the time and cross-sectional dimensions, respectively. Meanwhile, ε_t depicts a stochastic error component.

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Additionally, $\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5$ are the relevant coefficients of the enlisted explanatory variables, while φ_0 is the slope.

Hypothetically, green technology and green transition are positive predictors of load capacity factors. On the other hand, resource utilization, economic expansions, and urbanization are negative predictors of load capacity factors. Hence, the hypothetical relationships are expressed mathematically herein:

$$\varphi_1 = \frac{\partial LCF}{GreenTech} > 0, \varphi_2 = \frac{\partial LCF}{GreenTran} > 0, \varphi_3 = \frac{\partial LCF}{RUtil} < 0,$$
$$\varphi_4 = \frac{\partial LCF}{Expan} < 0, \varphi_5 = \frac{\partial LCF}{Urban} < 0$$

3.3 | Estimation Techniques

Several econometrics estimation protocols were relied upon for the novelty of the present study. Among them are sets of pre-estimation tools, estimation tools, and robustness test techniques. Particularly, the study evaluates the critical characteristics of the relevant series with summary statistics, correlation analysis, density plots, cross-sectional dependency (CD) tests, slope heterogeneity tests, stationarity tests, and long-term coevolution tests. Furthermore, the novel and recently introduced method of moment quantile regression is adopted for baseline evaluation of the relationship. Other techniques, including the fully generalized least squares (FGLS), panels corrected standard errors (PCSE), augmented mean group (AMG), as well as the cross-sectional autoregressive distributed lags (CS-ARDL), are robustness evaluators. Notably, adopting the novel panel-frequency domain Granger causality test represents another novel milestone in this present investigation.

3.3.1 | Cross-Sectional Dependency and Slope Heterogeneity Tests

A critical step in panel econometric evaluation protocols is the verification of cross-sectional dependencies among the relevant variables over time and across the cross-sections. This step serves several critical purposes, including the decision about the relevant generation of panel unit-root tests and the choice of appropriate coevolution test kits (Uche and Effiom 2021; Obiakor, Uche, and Das 2022; Uche 2022; Uche, Nwaeze, and Akonye 2023). Essentially, the *CD* test verifies the possible spillover of residuals from one country to another. On the other hand, the *SH* test verifies the potential heterogeneous or homogeneous slopes among the cross sections. Notably, the close economic ties of the cross-sections give room for error spillover and slope heterogeneity. Hence, ignoring these nuances could lead to biased estimates with consequential misleading inferences. For this purpose, the mathematical protocols of both the *CD* and *SH* tests are provided herein:

$$CD = \sqrt{\frac{2T}{n(n-1)}}\left(\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\rho_{j,T}\right) \tag{3a}$$

$$CDw = \sqrt{\frac{2}{Tn(n-1)}}\sum_{t=1}^{T}\sum_{i=2}^{n}\sum_{j=1}^{t-1}\left(w_t\varepsilon_{it}\right)\left(w_t\varepsilon_{it}\right) \tag{3b}$$

$$CD_{w+} = CD_w + \Delta_{nT} \tag{3c}$$

$$CD^* = \frac{CD + \sqrt{\frac{T}{2}\theta_n}}{1-\theta_n} \tag{3d}$$

$$\Delta HT = (N)\frac{1}{2}(2k) - \frac{1}{2}\left(\frac{1}{N}S - k\right) \tag{4a}$$

$$\Delta AHT = (N)\frac{1}{2}\left(\frac{2k-(T-k-1)}{T+1}\right)\frac{1}{2}\left(\frac{1}{N}S - k\right) \tag{4b}$$

where Equations (3a) and (3b) are mathematical notations of the Pesaran (2015) average correlation cross-sectional dependency tests. At the same time, Equations (3c) and (3d) are mathematical expressions of the newly introduced Juodis and Reese (2021) CDw and Fan, Liao, and Yao (2015) weak CDw + tests, respectively. Notably, Pesaran et al. (2021) introduced the bias-corrected cross-sectional dependency test to overcome the challenges imposed by the weaknesses of the previous *CD* tests. Likewise, the newly introduced *CD* test technique (CD*) provides direct corrections on the asymptotic biases in existing *CD* tool kits.

Remarkably, $\theta_n = 1 - \frac{1}{n}\sum_{i=1}^{n}\varphi_{i,n}^2$ is the function that confirms the existence of CD* in the mathematical framework (Equation 3d). Additionally, Equations (4a) and (4b) depict the functional forms of the Pesaran and Yamagata (2008) *SH* test. Accordingly, ΔHT and ΔAHT depict the nominal delta tilde and the adjusted delta tilde of the transnational slopes, respectively.

3.3.2 | Panel Stationarity Tests Techniques

The study relied on sets of second and third-generation panel stationarity test toolkits in a bid to verify both the orders of integration of the series as well as the presence of structural breaks. Notably, the veracity of the empirical inferences arising from the empirical estimates is questionable when these factors are ignored. On this background, the current study considered the dimensions of the cross-section Im, Pesaran & Shin (CIPS [Im, Pesaran, and Shin 2003]), the Pesaran cross-section augmented Dickey-Fuller (CADF [Pesaran 2007]), and the Karavias & Tzavalis (KT [Karavias and Tzavalis 2014]). Remarkably, while the CIPS and CADF are second-generation panel stationarity test protocols, the KT is a third-generation protocol that probes the effects of structural breaks on relevant panel datasets. However, the second and third-generation panel stationarity test toolkits are formidable in the face of cross-sectional dependencies and slope heterogeneities. Henceforth, the functional schemes of the relevant panel stationarity test kits are provided herein.

$$CIPS = \frac{1}{N}\sum_{i=1}^{N}\partial_{,}(N,T) \tag{5}$$

$$\Delta_{it} = \sigma_{it} + \beta_{it-1} + \theta_1 T + \sum_{j=1}^{N}\partial_{ij}\Delta\times_{it-1} + \mu_{it} \tag{6}$$

$$\phi' = \left(\sum_{i=1}^{n}\theta'_{t-1}\theta_m^{(\lambda)}\theta_{i-1}\right)^{-1}\left(\sum_{i=1}^{n}\theta'_{t-1}\theta_m^{(\lambda)}\theta_{i-1}\right), m(M1,M2) \tag{7}$$

Herein, Equations (5)–(7) are mathematical representations of CIP, CADF, and KT panel stationarity test techniques,

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respectively. Furthermore, in the case of the KT technique, the null hypothesis expresses that some panel series are unit-root processes. However, the alternative hypothesis suggests that some or all the panel time series are stationary processes. Likewise, in Equation (7), $\theta_m^{(\lambda)}$ is the transformation matrix of the relevant panel datasets.

3.3.3 | Panel Long-Run Coevolution Test Techniques

As earlier noted, the relevant panel series was checked for possible long-run convergence. Verifying possible long-term convergence of series is a notable step in panel econometric processes. Moreover, the long-term coevolution of the panel series enriches the veracity and validity of the empirical estimates. For this purpose, this study employed the Westerlund (2007) error-correction panel cointegration technique and the novel Banerjee and Carrion-i-Silvestre (2017) procedure. Accordingly, Erdoğan et al. (2020) highlighted that the restrictions imposed by the Westerlund (2007) procedure are eliminated by the flexibility of the Banerjee and Carrion-i-Silvestre (2017) protocol. Notably, both techniques are common correlated effect estimators, and they are rigorous for weak, semi-strong, and strong cross-sectional dependencies. The null hypothesis of the absence of long-run coevolution is tested against the alternative of the presence of long-run coevolution. Remarkably, the application of the newly introduced Banerjee and Carrion-i-Silvestre (2017) panel cointegration procedure marks another significant step that enriches the novelty of this study.

3.3.4 | Econometrics Techniques

The present study relied on a plethora of novel panel estimators for its empirical engagements and inferences. Among them, the method of moments quantile regression (mmqr) procedure of (Machado and Santos Silva 2019) represents the baseline estimator. On the other hand, both the fully generalized least squares, the Prais–Winsten regression correlated panels corrected standard errors (PCSEs), the augmented mean group (Eberhardt and Teal 2010), and the cross-sectional autoregressive distributed lags (CS-ARDL[Chudik and Pesaran 2015]) are the relevant robustness test techniques. For brevity, we emphasized the baseline estimator—the mmqr panel procedure.

3.3.5 | The Method of Moments Quantile Regression Technique

Accordingly, the mmqr panel estimator is a time-variant panel tool kit akin to Machado and Santos Silva (2019). The mmqr panel estimator is robust in the face of heteroscedasticity and outliers. According to Machado and Santos Silva (2019), the mmqr verifies more comprehensively, through the methods of the moment, the steps and possible effects of the changes in the covariates on the predicted variable across the distributions. The procedure also uncovers heterogeneous distributions within conditional distributions of the outcome variable (Bista and Khan 2023; Guan et al. 2023; Jahanger et al. 2023; Pata and Samour 2022; Uche, Odionye, and Ngepah 2024).

Unlike other conventional quantile regression procedures, the mmqr toolkit is vigorous to individual country-specific fixed effects that resist incidental parameter challenges across the distributions (Bista and Khan 2023). Furthermore, the mmqr technique is sensitive to variables that deviate from normal distributions. Another unique feature of the mmqr is that it predicts the interactions of variables at the location and the scales, as well as the lower, middle, and upper quantiles. In this context, the model can predict the short-run, intermediate and long-run effects of green technologies and green transitions on load capacity factor in BRICS economies. Based on insights gained from Machado and Santos Silva (2019), we provide the baseline location-fixed effects quantile procedure $Q(\tau \mid X)$ accordingly in Equation (8).

$$Q_{\Upsilon}\left(\tau \mid X_{it}\right) = \left(\alpha_i + \theta_i \delta_i\right) + X_{it}'\beta + K_{it}'\gamma\rho(\tau) \tag{8}$$

where $Q_{\Upsilon}\left(_{\tau} \mid X_{it}\right)$ depicts the conditional quantile distributions of the predicted variable. X_{it} is the vector of all the relevant explanatory and control variables. $\alpha_i(\tau) = \alpha_i + \theta_i\delta_i(\tau)$ depicts the scalar coefficient of the $\tau - th$ quantile of the individual i specific fixed effects. K_{it}' is the K-vector, while $\rho(\tau)$ represents the $\tau - th$ quantile formulated through an optimization procedure depicted in Equation (9).

$$\min_{\theta} \sum_{i} \sum_{t} \sigma_{\tau}\left(F_{it} - \left(\delta + K'_{it}\gamma\right)\theta\right) \tag{9}$$

where $\rho_{\tau}(A) = (\tau - 1)AI\{A \leq 0\} + \tau AI(\{A > 0\})$ depicts the quantile conditional check function. Thus, this unique time-varying panel estimator would effectively harmonize any potential deviation from normal distributions, structural breaks, and time variations.

3.3.6 | Panel Frequency-Domain Granger Causality Procedure

Based on notable insights from Aydin (2023), this study applied the panel (multi-country) frequency domain Granger causality test. This notable step is undertaken to enrich the novel perspective of this investigation further. The newly introduced panel frequency-domain Granger causality technique is attributable to Croux and Reusens (2013). Prior studies ignored this unique panel Granger causality procedure that boasts several unique attributes.

Specifically, unlike other Granger causality procedures, the multi-country frequency-domain Granger causality procedure considers the causal relationship among panel series over a distribution. It checks the causal relationship at the least, moderate and high fluctuating frequencies (Croux and Reusens 2013; Aydin 2023). Traditional time and frequency-domain Granger causality frameworks (Breitung and Candelon 2006; Shi, Hurn, and Phillips 2020) are insensitive to multi-country peculiarities. However, this novel framework introduced by Croux and Reusens (2013) provided the flexibility to assess causal effects at different frequencies over time in a panel setting. By applying the spectral density function, the multi-country frequency-domain Granger causality technique can dictate periodic fluctuations in a relationship. The Croux and Reusens (2013) technique follows a seemingly unrelated regression (SUR) process. Thus,

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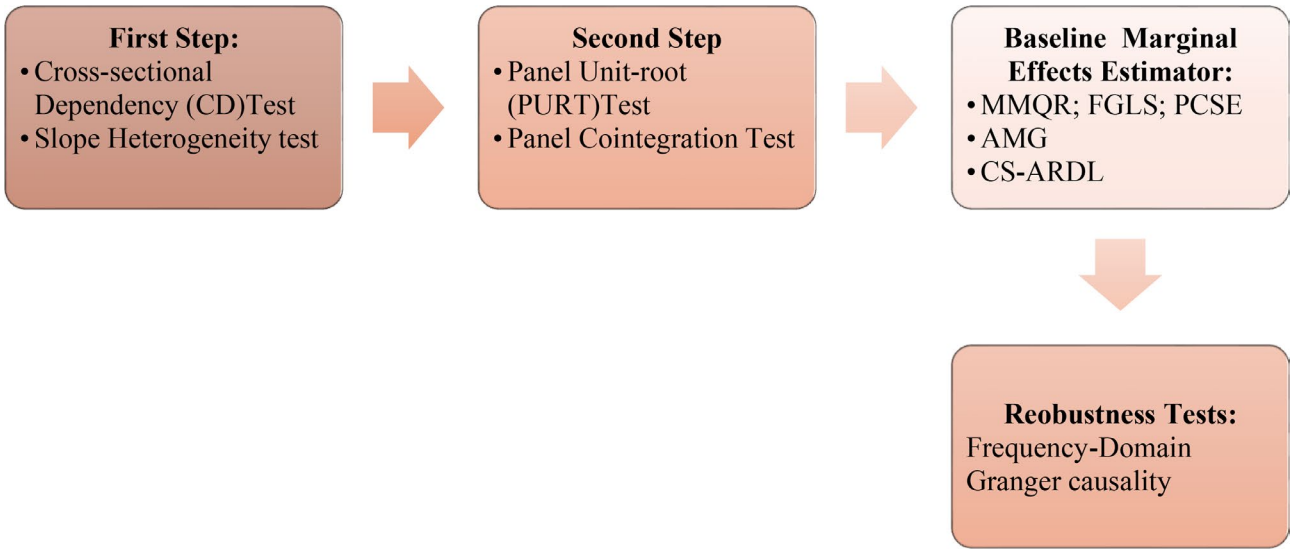


FIGURE 3 | Methodological scheme.

TABLE 2 | Descriptive.

	Load capacity factor	Green technology	Green transition	Resource utilization	Economic expansion	Urbanization
N	210	210	210	210	210	210
Mean	1.28	10.1	5.95	5.93	27.0	18.7
Standard deviation	1.37	4.12	1.51	4.68	1.59	1.03
IQR	0.924	4.16	1.58	5.12	1.80	1.08
Minimum	0.226	1.56	0.565	0.864	21.1	16.5
Maximum	5.22	33.3	8.93	21.5	30.5	20.6
Skewness	1.52	1.81	−0.971	1.43	−1.16	−0.384
Std. error skewness	0.168	0.168	0.168	0.168	0.168	0.168
Kurtosis	0.981	7.14	0.887	1.29	4.04	−0.526
Std. error kurtosis	0.334	0.334	0.334	0.334	0.334	0.334
Shapiro–Wilk	0.714	0.880	0.911	0.824	0.888	0.954
Shapiro–Wilk p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Equation (10) depicts the typical mathematical framework of Croux and Reusens (2013) panel frequency-domain Granger causality technique.

$$X_{i,t} = \sum_{j=1}^{p} \theta_{i,j} X_{i,t-j} + \sum_{j=1}^{p} \partial_{ij} Y_{i,t-j} + \varepsilon_{i,t} i = 1, 2, 3, \ldots N \quad (10)$$

where θ_{ij} and ∂_{ij} are, respectively, the coefficients of $X_{i,t-j}$ and $Y_{i,t-j}$. $X_{i,t-j}$ and $Y_{i,t-j}$ are the respective variables of country i at time t, while $\varepsilon_{i,t}$ is the white-noise error component. N and p are respectively, the number of countries and lag lengths.

Accordingly, the panel frequency-domain Granger causality test applies some conditions used to accept or reject the null hypothesis. In this context, the null hypothesis suggests the absence of Granger causal effects at ω frequency.

$$\sum_{j=1}^{p} \partial_{ij} \cos(\sigma\omega) = 0_i = 1, 2, \ldots N \quad (11)$$

$$\sum_{j=1}^{p} \partial_{ij} \sin(\sigma\omega) = 0_i = 1, 2, \ldots N \quad (12)$$

Consistent with the single-country framework, the incremental *R-square* is defined in Equation (13).

$$\text{Incremental } R_i^2 = R^2 - R_*^2 \quad (13)$$

where R^2 and R_*^2 illustrate the restricted and unrestricted SUR models that are consistent with the McElroy *R-square* values. Notably, the *R-square* measures the goodness of fit in a typical SUR protocol. Accordingly, the null hypothesis of no Granger

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FIGURE 4 | Correlation heatmap.

causal effects at ω frequency in all cross-sections is rejected at level α when:

$$Increamental\ R_1^2 > F_{(2G,G(T-2p),1-\alpha)}\frac{2G}{G(T-2\rho)}\left(1-R^2\right) \quad (14)$$

where $F_{(2G,G(T-2p),1-\alpha)}$ is α the critical F distribution factor. $2G$, GT, and 2ρ is the number of conditional restrictions, number of observations, and the total estimated coefficients' values, respectively. Figure 3 is the infographic demonstration of applicable methodological steps peculiar to this study.

4 | Analysis and Discussions

4.1 | Preliminary Test

Table 2 showcases some common features of the dataset and offer a comprehensive view of their central tendencies, dispersions, and ranges.

All the selected variables display significant dispersion from their mean values, indicating substantial variability and volatility. This underscores the importance of examining time-variant panel estimators for the BRICS countries. The coefficient of skewness shows that most variables are positively skewed, including LCF, Green Technology, Green Transition, and Resource Utilization. In contrast, Economic Expansion and Urbanization exhibit negative skewness. The kurtosis values suggest that the distributions generally have lighter tails, and a flatter peak compared to a normal distribution, indicating a platykurtic nature. However, Green Technology has a kurtosis value greater than three, suggesting a heavier tail and a higher tendency for outliers. Shapiro–Wilk test results indicate that all variables follow a non-normal distribution. Consequently, relying on panel estimators insensitive to time variations would likely result in misleading conclusions and biased inferences. Therefore, the adoption of appropriate time-variant panel procedures is well justified to ensure accurate analysis and results.

Furthermore, Figures 4 and 5 illustrate the correlation heatmap and density plots, respectively. The figures investigate the potential multicollinearity and the time-varying nature of the variables under study. First, Figure 4 explores the correlation matrix, revealing that multicollinearity is not a significant threat to our empirical analysis. The highest recorded correlation coefficient is 0.43, which does not suggest multicollinearity, as it pertains to a dependent–independent relationship. This confirms the veracity of these pre-estimation outcomes. Multicollinearity in a regression model can lead to incorrect conclusions; therefore, we subjected our dataset to time-varying analysis. Figure 5 presents the outcomes of the density plots of the dataset, which are consistent with the Shapiro–Wilk test results. This consistency supports the fact that the series are not normally distributed.

This study employs five types of Cross-Sectional Dependence (CD) tests, as presented in Table 3, to obtain more reliable estimates and draw informed conclusions. The tests used include Pesaran (2007), Pesaran (2015), Pesaran et al. (2021), Juodis and Reese (2021), Fan, Liao, and Yao (2015), and Pesaran et al. (2021). The results from these CD tests provide evidence against the hypothesis of both cross-sectional independence and slope homogeneity among the specified nations. This finding indicates a significant degree of economic integration, interconnections, international alliances, and spillover effects among the BRICS countries. Consequently, selecting panel estimators that account for these complexities is crucial.

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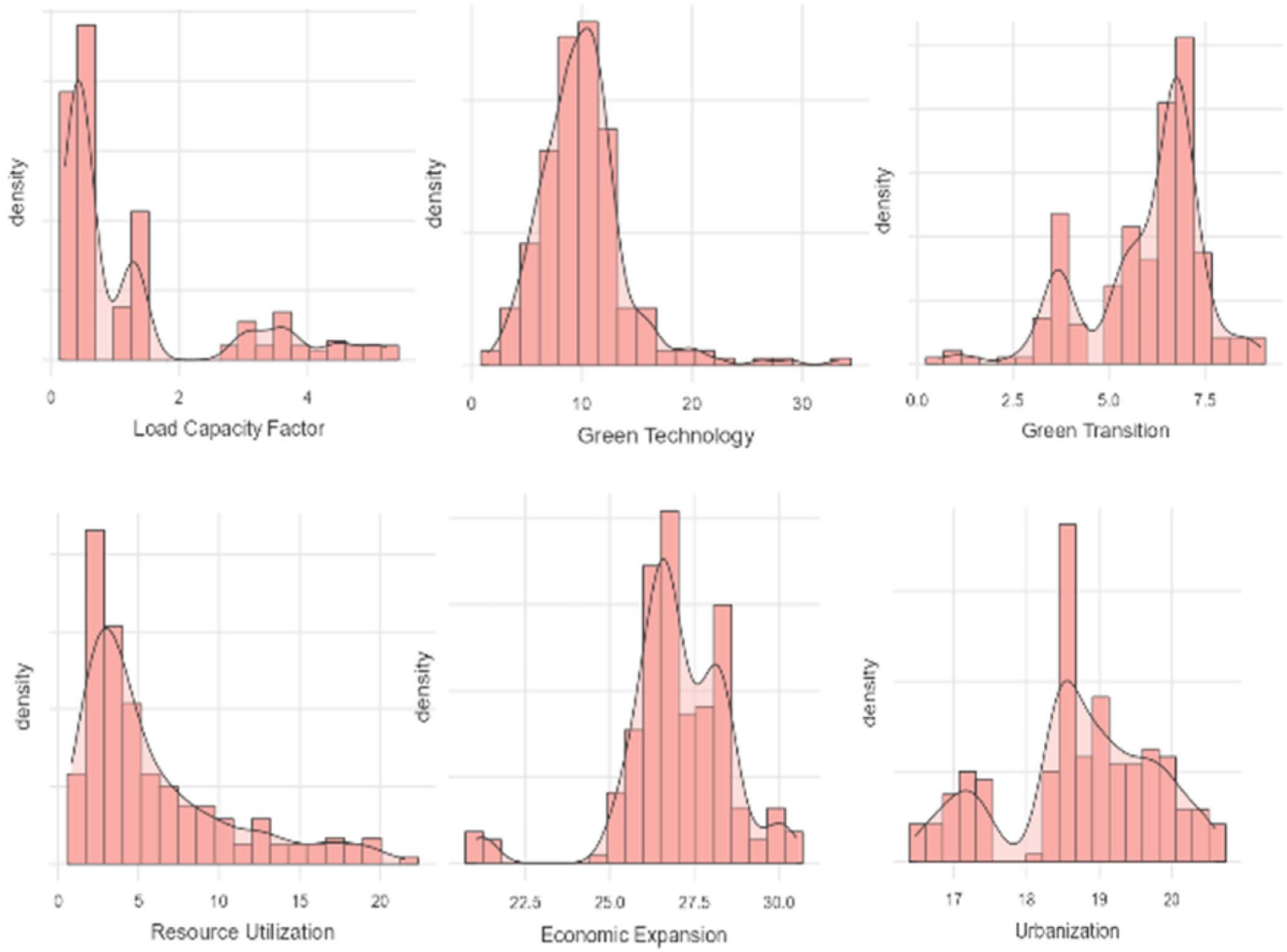


FIGURE 5 | Density plots.

TABLE 3 | CD and SH tests.

Variables	CD: Pesaran (2007 Karavias, Y. & Tzavalis, E. (2014))	CD: Pesaran (2015); Pesaran et al. (2021)	CDw: Juodis and Reese (2021)	CDw+: Fan, Liao, and Yao (2015)	CD*: Pesaran & Xie
LCF	9.84***	9.841***	−0.50	41.60***	0.30
GreenTech	1.75**	1.746**	−0.62	13.67***	1.83*
GreenTran	16.72***	16.725***	5.43***	58.32***	0.42
RUtil	3.32***	3.319 ***	−2.20**	25.43***	0.73
Expan	18.05***	18.047***	3.03***	60.10***	0.48
Urban	16.23***	16.229***	1.83*	53.14***	0.45
Slope heterogeneity test					
Delta	5.848***	0.000	Adj.	6.406***	0.000

***$p < 1\%$.
**$p < 5\%$.
*$p < 10\%$.

4.2 | Panel Unit-Root Test (PURT)

In Table 4, both traditional (second generation) and modern (third generation) stationarity techniques were employed, specifically the CIPS, PESCADF, and Karavias, Y. and Tzavalis, E. (2014) procedures, to determine the unit root status of the dataset. The analysis revealed that the dataset achieved stationarity after first differencing. Furthermore, the series were significantly influenced by structural breaks, including the economic expansions of 1986 and the impact of COVID-19 in 2020. These structural breaks necessitated the application of third generation unit root procedures, such as the Karavias, Y. and Tzavalis, E. (2014) method.

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4.3 | Cointegration

In this study, Table 5 presents the results of cointegration tests conducted using the techniques developed by Westerlund (2007) and Banerjee and Carrion-i-Silvestre (2017). These tests confirm the presence of a long-run relationship among the variables. The establishment of this long-run relationship paves the way for further empirical analysis to investigate the cause-effect dynamics in the current study.

4.4 | Regression Results

This section employs the MMQreg estimator to address distributional asymmetry and heterogeneous effects in the dataset. Table 6 presents the regression results analyzing the relationship between Green Innovations, Green Transitions, and Load Capacity Factors (Ecological Sustainability). A key finding is the consistency of the results across all quantile distributions, both at the central point of the data (location) and the average spread of the data (scale). This means that the observed pattern, such as the positive self-reinforcement, holds true not just at the central tendency and dispersion, but also across different parts of the distribution, including the lower, middle, and upper quantiles. The estimated coefficient for green technology is positive but statistically insignificant across most quantiles (from qtile_25 to qtile_95), with the exception of an insignificant negative effect at qtile_5. This suggests that while green technological innovations have the potential to enhance the load capacity factor (LCF) in BRICS economies, the relationship is not strong enough to be conclusive. The positive yet insignificant results indicate that initial improvements in green technology could eventually lead to further gains, creating a reinforcing positive trend over time. Consequently, it is crucial for countries to implement effective policies that consistently improve their LCF. This finding is consistent with previous research by Uche, Okere, and Das (2023) for India, and Alam, Destek, and Haque (2024) for BRICS nations, and it moderately supports our hypothesis of a positive association between green technological innovations and the load capacity factor. These findings suggest that BRICS countries could effectively prioritize achieving environmental sustainability through green technologies. To do this, it is crucial for these nations to demonstrate strong commitments to addressing inadequate energy transitions and insufficient attention to environmental matters in global technological innovation. This can be achieved by implementing and enforcing policies that expressly support the deployment of green technologies, contingent upon the necessary policy frameworks.

In contrast to earlier findings, green transitions continue to be a crucial element in enhancing environmental quality in BRICS countries. The results indicate a substantial positive coefficient for green transitions across multiple quantiles, with the exception of the scale and qtile_5. Therefore, the null hypothesis positing a positive correlation between green technologies and the load capacity factor is dismissed. The estimated results suggest that the advantageous impacts of energy transitions differ across pertinent quantiles; nonetheless, there are significant discrepancies

TABLE 4 | Stationarity test.

	CIPS		PESCADF		KT	
Series	**Order-zero**	**Order-one**	**Order-zero**	**Order-one**	**MinZ-Stat**	**Break date**
LCF	−2.826**	−5.789***	−2.541**	−5.119***	−9.357***	1981
GreenTech	−5.272***	−6.190***	−4.826***	−6.190***	−19.359***	2020
GreenTran	−0.734	−5.773***	−0.906	−4.120***	−17.594***	2020
RUtil	−2.611**	−5.611***	−2.228	−5.242***	−11.178***	1981
Expan	−1.955	−5.057***	−1.886	−3.884***	−19.475***	1986
Urban	−1.241	−2.570**	−1.681	−2.432**	−20.327***	2020

***$p < 1\%$.
**$p < 5\%$.
*$p < 10\%$.

TABLE 5 | Long run coevolution tests.

Westerlund (2007)				
Model	***Gt***	***Ga***	***Pt***	***Pa***
Lcf = f(x)	−2.190	−8.631**	−5.888*	−15.131**
Banerjee and Carrion-i-Silvestre (2017)				
	CIPS*	**1% crit. value**	**5% crit. value**	**10% crit. value**
Lcf = f(x)	−5.713***	−2.55	−2.33	−2.21

***$p < 1\%$.
**$p < 5\%$.
*$p < 10\%$.

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TABLE 6 | Regression estimates.

Series	Location	Scale	Quantile grids				
			qtile_5	qtile_25	qtile_50	qtile_75	qtile_95
GreenTech	0.028	0.014	−0.002	0.016	0.024	0.037	0.062
GreenTran	0.023***	0.292	0.394	0.774***	0.927***	0.196***	0.697***
RUtil	−0.110***	−0.049	−0.003	−0.067	−0.094***	−0.139***	−0.224**
Expan	−0.115	−0.097	0.092	−0.033	−0.084	−0.173**	−0.340***
Urban	−0.277***	−0.432*	−0.346	−0.907***	−0.135***	−0.532***	−0.274***
C	22.610***	9.884*	1.355***	14.174***	19.362***	28.454***	45.388***

***$p < 1\%$.
**$p < 5\%$.
*$p < 10\%$.

in ecological governance among these nations, as illustrated in Figures 1 and 2. Moderate discrepancies are observed at locations qtile_25 and qtile_50, whereas enhancements are noted at qtile_75 and qtile_95 in the load capacity factor. These results align with other research (Adebayo and Samour 2023; Hossain et al. 2023; Hossain, Rej, and Hossain 2023). The BRICS nations must continue to advocate for measures that ensure continuity and consistency within these dynamics. The decline observed in the middle to higher quantiles requires attention, and continuous monitoring and reassessment will aid these nations in maximizing the benefits of energy transitions for improved environmental quality.

To analyze the unique policy implications for the control variables of resource utilization, economic growth, and urbanization, multiple classifications of anthropogenic factors affecting environmental sustainability were established. These variables adversely affected the load capacity factor in BRICS nations. The decline in load capacity factor was significantly influenced by resource utilization and economic growth, although urbanization exerted no effect on the marginal load capacity factor in the area. At the local level, resource consumption and economic growth were observed to diminish environmental quality by 11% and 28%, respectively. The quantile analysis of the control variables indicated that the detrimental effect of urbanization reached its zenith at the 25th percentile, representing approximately 91% of the decrease in ecological load capacity among BRICS nations. The detrimental impacts of resource consumption and economic growth were most evident at the upper quantile (95th percentile), resulting in a reduction of environmental sustainability by 22% and 34%, respectively. These results align with the study performed by Opuala, Omoke, and Uche (2023). The results demonstrate that BRICS economies have compromised environmental quality in favor of resource exploitation, economic advancement, and urban expansion. To resolve this issue, it is imperative for these nations to adopt sustainable resource management policies and shift to renewable energy sources. Policies that emphasize environmental health over resource depletion, economic expansion, and urbanization are essential. This necessitates the integration of environmental sustainability measures with comprehensive protection criteria that all sectors must adhere to. Ongoing oversight by relevant governmental authorities is necessary to ensure compliance.

The quantile graphs (Figure 6) provide additional insight into the influence of the specified variables on load capacity factors in BRICS countries. These graphs visually highlight the modest improvements brought about by green technology advancements on load capacity factors. Furthermore, the figures illustrate the significant positive effects of the green transition across the quantile of load capacity factors.

The quantile plots provide a critical insight into the detrimental effects of resource utilization, economic expansion, and urbanization on the quantile of load capacity factors in BRICS nations. The plot clearly highlights the significant negative impacts of resource utilization and urbanization, suggesting that these factors undermining environmental sustainability. This analysis underscores the urgent need for BRICS nations to reassess their development strategies. Current policies that prioritize economic growth and urban expansion over environmental health are proving to be counterproductive. To rectify this, these nations must implement policies that prioritize sustainable resource management and environmental health. The judicious use of resources and strategic urban planning are essential to ensure that development does not come at the expense of environmental integrity. Without such measures, BRICS nations risk perpetuating a cycle of unsustainable development that could have long-term negative consequences for both the environment and their economies.

4.5 | Robustness Analysis

Table 7 presents several panel estimations to verify the results of previous analyses, serving as a robustness check. We used FGLS, PCSE, AMG, and CS-ARDL methods with the STATA algorithm to ensure that the estimates and inferences from the dataset are reliable and robust, especially for panel data with complex error structures and dependencies. The results consistently align with the MMQreg analysis, confirming the robustness and stability of our empirical approach. The robustness tests revealed both moderate and strong positive impacts of green technologies and transitions on the Load Capacity Factor (LCF). Green technologies demonstrated statistically significant short-term positive impacts on LCF, indicating that these advances can initially improve environmental quality. Nonetheless, these beneficial effects were ephemeral, reflecting the rudimentary stage of green technological innovation

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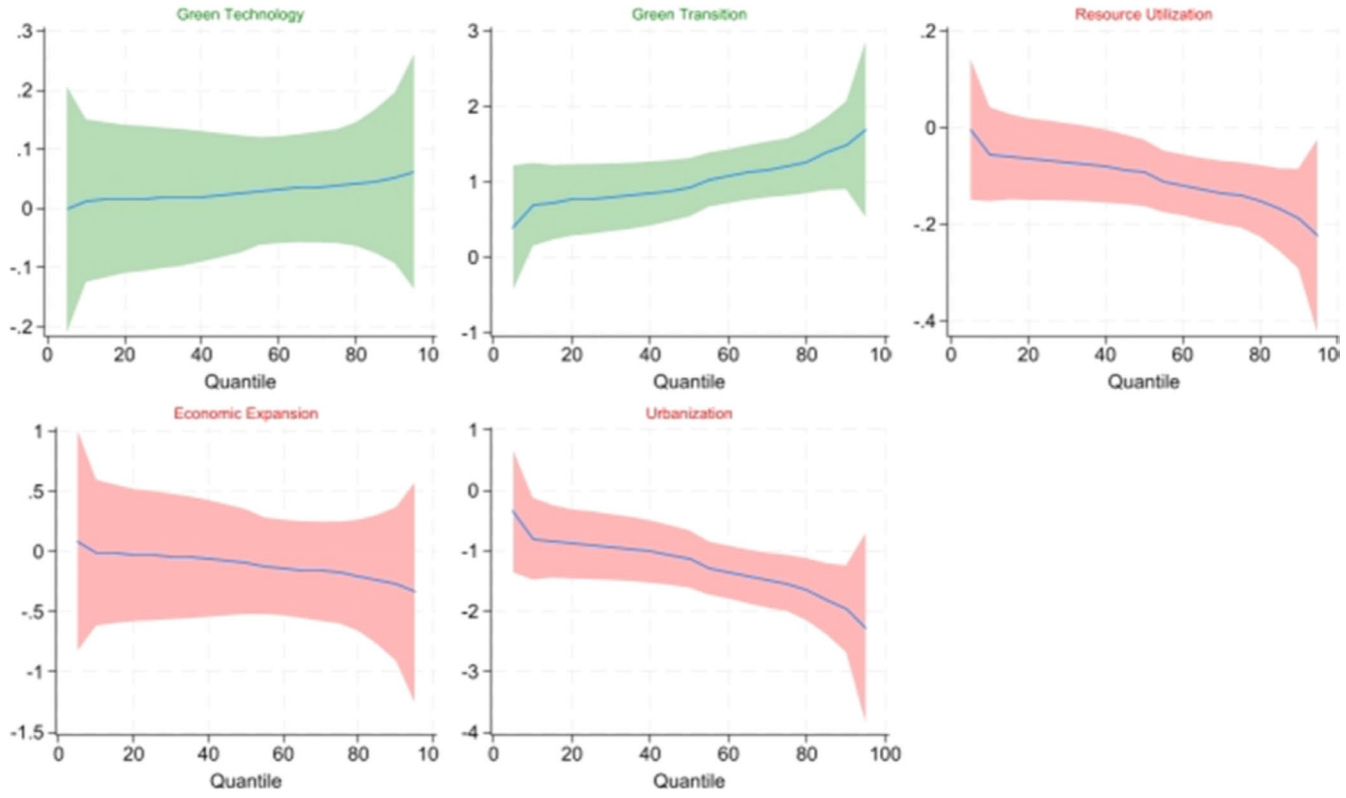


FIGURE 6 | Quantile distributions plots.

TABLE 7 | Re-estimation tests.

				CS-ARDL	
Variables	**FGLS**	**PCSEs**	**AMG**	**Short-run**	**Long-run**
Constant	18.461***	10.709***	4.282**	0.253***	—
GreenTech	0.009*	0.007	0.002**	0.006*	0.004
GreenTran	0.689***	0.367***	0.023*	0.166***	0.147*
RUtil	−0.020*	−0.007*	−0.003	−0.006**	−0.005**
Expan	−0.140***	−0.023	−0.042***	−0.021**	−0.018*
Urban	−0.933***	−0.584***	−0.098**	−0.095**	−0.941**

***$p < 1\%$.
**$p < 5\%$.
*$p < 10\%$.

in BRICS nations. Conversely, green transitions shown a marked decline in their beneficial effects from the short term to the long term. This reduction reveals discrepancies in policy execution and insufficient collaborative efforts, emphasizing the necessity for continuous policy alignment. Furthermore, the comprehensive research validated the adverse impacts of control variables, including resource consumption, economic growth, and urbanization, on environmental quality in BRICS nations.

These findings underscore the necessity of persistent and concerted legislative initiatives to alleviate these adverse effects and foster long-term environmental sustainability. This study advances two burgeoning domains of research in the literature. The initial set of studies, comprising research by Andrew et al. (2024), Pata et al. (2023), Adebayo and Kirikkaleli (2021), and Rout, Gupta, and Sahoo (2022), indicates that green technologies exert a negligible influence on the load capacity factor (LCF). These findings indicate that although green technologies diminish LCF, their effect on ecological sustainability is negligible or inconsequential. The subsequent cohort of studies, comprising Pata et al. (2023), Samour et al. (2023), and Ullah et al. (2023), indicates that the beneficial impacts of green transitions on LCF wane over time. Studies conducted by Huilan et al. (2022) and Pata and Samour (2022) indicate discrepancies in policy execution and an absence of coordinated initiatives to maintain these transitions. Although prior research predominantly endorses the notion that green technologies and transitions improve environmental performance, a significant gap exists in the literature concerning their effects on LCF in BRICS nations. This study addresses that gap by demonstrating that green transitions provide substantial short-term advantages for environmental quality, economic growth, and public support. Nonetheless, these beneficial effects may diminish in the long run

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owing to technological, economic, and policy obstacles. To guarantee the longevity of these advantages, it is essential to enact adaptive policies that mitigate the adverse impacts of these variables and promote ongoing innovation.

4.6 | Beyond the State of the Art Using Granger Causality Test

This study offers a distinctive chance to elucidate the potential causative relationship between load capacity factor (LCF) and specific variables, employing the panel frequency-domain Granger causality test—an novel approach that has been largely neglected in prior research. This time-varying Granger causality approach presents a novel and significant perspective, yielding discoveries that can stimulate further research and fulfill the study's final purpose. The graphical outcomes of the panel frequency-domain Granger causality test, illustrated in Figure 7, display a plot of incremental R-squared values vs. frequencies. The results suggest that the control factors, green technology, and green transitions have predictive potential for the distributions of load capacity components in BRICS, as evidenced by the frequency-domain Granger causality plots.

The panel frequency-domain Granger causality test yielded numerous critical discoveries with substantial policy implications. The causality charts in BRICS demonstrated time-sensitive effects among the specified factors and the load capacity factor (LCF). Green transitions were specifically identified as predictors of LCF across slowly, moderately, and rapidly varying components, demonstrating causal links across all LCF distributions, hence contradicting the null hypothesis. This indicates that green transitions are a significant predictor of LCF in BRICS nations. To enhance LCF, these nations must dedicate themselves to more vigorous green transition activities. Conversely, green technology impacted LCF in multiple ways, especially at the average fluctuating component, highlighting variations in the implementation of green technology among BRICS countries. This underscores the necessity for intensified initiatives in both the advancement and use of green technology to improve LCF in the region.

5 | Conclusion and Recommendations

The transition to clean technology facilitates global environmental sustainability by significantly mitigating environmental degradation and decarbonizing the global economy. The necessity and feasibility of this transition are emphasized by the UN SDG goals. Although environmental variables are commonly referenced in current literature, the notions of LCF, green technology, and green transition have been significantly neglected. LCF provides a holistic metric by addressing both the demand and supply dimensions of environmental health. This study examines the influence of advancements in green technology and transitions on LCF in BRICS nations, while also accounting for the synergistic impacts of resource consumption, economic expansion, and urbanization.

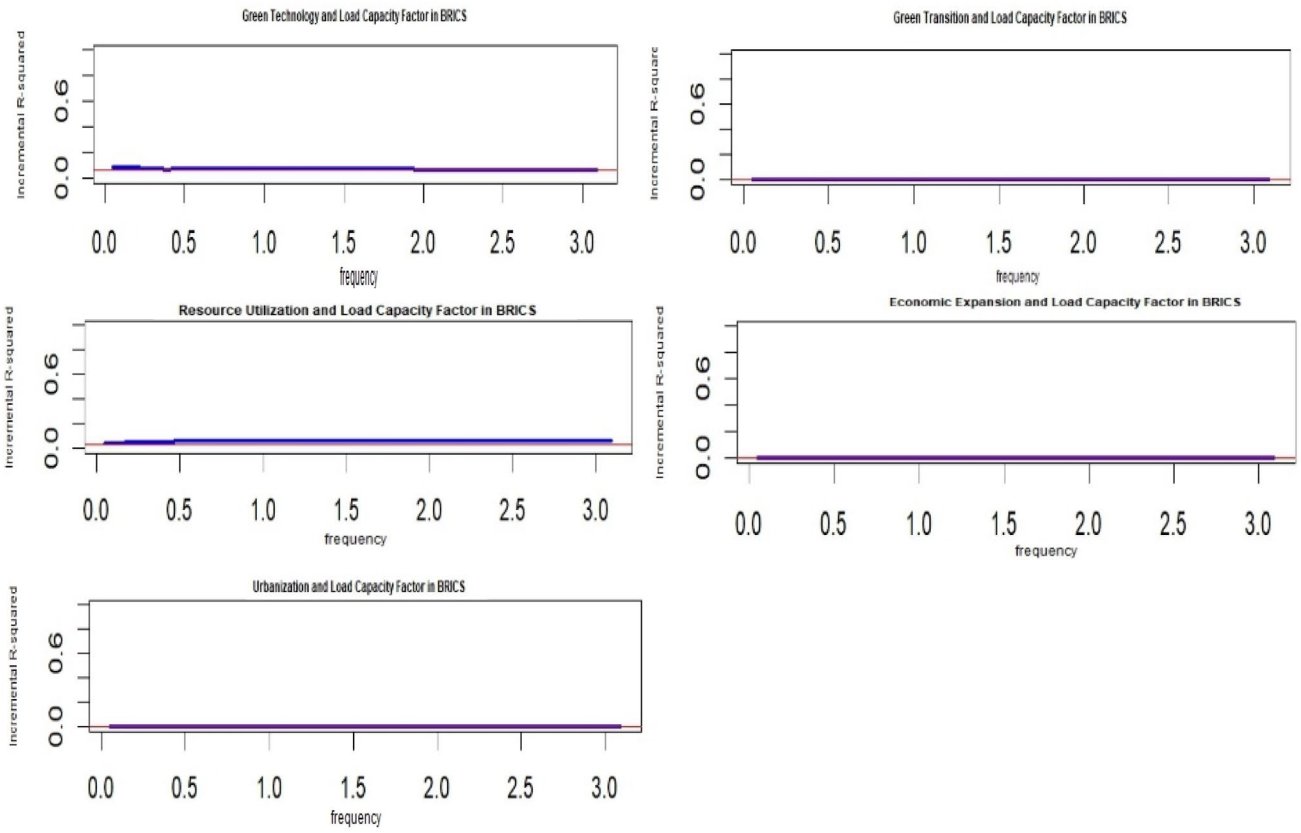


FIGURE 7 | Panel frequency-domain Granger causality plots.

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The analysis utilized multiple techniques, including MMQreg, FGLS, PCSE, AMG, CS-ARDL, and panel frequency-domain Granger causality, on a panel of 49 African economies from 1980 to 2021. The results are threefold: (i). Green technology exerts a positive albeit statistically negligible influence on load capacity factors across the majority of quantiles, suggesting its potential to promote ecological sustainability in BRICS nations. (ii) Green transitions provide a beneficial and statistically significant effect on environmental quality across most quantiles, underscoring their significance despite certain anomalies. (iii) Control variables, including resource utilization and economic growth, exerted a substantial negative influence on load capacity factors, although urbanization had a negligible effect, particularly at elevated quantiles.

A crucial policy implication is for BRICS nations to prioritize investments in green technologies. Policymakers should focus on the continuous deployment of innovations such as electric vehicles (EVs) and explore the full potential of other green technologies. By doing so, these nations can reduce environmental impact, enhance sustainability, and drive progress toward long-term environmental goals. Furthermore, a key policy option for promoting green transitions is to increase investment in renewable energy, regenerative agriculture, and utilize economic policy instruments such as taxes and tradable permits. While green transitions have a positive and statistically significant impact on environmental quality across most quantiles, challenges remain in implementing effective policies, particularly in tailoring country-specific policy mixes for a just transition. To address these challenges, policy options should focus on mobilizing additional resources for a socially just transition, leveraging price regulation and financial instruments to ensure the equitable distribution of benefits and support long-term environmental sustainability. Finally, private partnerships and engagement are key to achieving this policy objective. Therefore, by integrating the private sector as a collaborator, policymakers can unlock new opportunities for driving sustainable environments.

While the study provides valuable insights into the role of green technology in achieving environmental sustainability in BRICS nations, its findings reveal certain limitations. Notably, the statistically insignificant impact of green technology on load capacity factors across various quantiles remains unclear, suggesting that the effect may be weaker than anticipated or masked by other factors. Although advanced statistical techniques, such as quantile regression and panel series analysis, were employed to assess these effects, challenges in precise evaluation persist due to the complexity of the underlying relationships. These limitations point to the need for more refined models and methods to better capture the nuanced impacts of green technology on environmental sustainability. To address these challenges and improve the understanding of green technology's role in BRICS economies, further research is essential. Future studies should consider exploring additional variables or alternative methodologies that could provide a more accurate assessment of green technology's impact on load capacity factors. By focusing on these areas, future research can offer more concrete guidance on how BRICS nations can fully harness the potential of green technology for sustainable development.

Conflicts of Interest

The authors declare no conflicts of interests.

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