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THE NEXUS BETWEEN SUSTAINABLE DEVELOPMENT, GREEN ENERGY, AND GREEN TECHNOLOGY IN BRICS COUNTRIES: A HETEROGENEOUS PANEL CAUSALITY APPROACH

BRICS ÜLKELERİNDE SÜRDÜRÜLEBİLİR KALKINMA, YEŞİL ENERJİ VE YEŞİL TEKNOLOJİ İLİŞKİSİ: HETEROJEN PANEL NEDENSELLİK YAKLAŞIMI

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Abstract: Reaching the Sustainable Development Goals (SDGs) requires a dramatic balance of economic growth, environmental limits, and social well-being. This approach has transformed sustainable development into a multidimensional issue rather than a strictly macroeconomic one. To examine this dynamic, this study employs a novel index that combines human development and ecological impact, spanning annual data from the BRICS economies from 1992 to 2022. Accordingly, it applies a heterogeneous panel methodology that explicitly controls for cross-sectional dependence and slope-parameter heterogeneity. Empirical findings reveal country-specific patterns. Initially in China, green energy drives sustainable development, and there is strong unidirectional causality from sustainable development to green technology. In India, sustainable development and green energy influence each other mutually. By contrast, Brazil and South Africa display bidirectional causality from sustainable development to green technology. Russia also shows that there is bidirectional causality from green technology to sustainable development. Ultimately, this study fills a critical gap in the literature by clarifying how the green transition supports overall sustainable development. The results provide practical insights for policymakers on effective long-term sustainability strategies and precautions.

Keywords: Sustainable Development, Environmental Sustainability, Green Energy, Green Technology, BRICS

JEL Codes: C50, P28, Q01, Q43

Öz: *Sürdürülebilir Kalkınma Hedefleri'ne (SKH) ulaşmak, ekonomik büyüme, çevresel sınırlar ve sosyal refah arasında hassas bir denge kurulmasını gerektirir. Bu yaklaşım, sürdürülebilir kalkınmayı sadece makroekonomik bir mesele olmaktan çıkarıp çok boyutlu bir konuya dönüştürmüştür. Bu dinamiği incelemek amacıyla bu çalışma, insani gelişme ile ekolojik etkiyi birleştiren ve 1992'den 2022'ye kadar BRICS ekonomilerine ait yıllık verileri kapsayan yeni bir endeks kullanmaktadır. Buna uygun olarak, çalışma, kesitsel bağımlılığı ve eğim parametresi heterojenliğini kontrol eden heterojen panel metodolojisini uygulamaktadır. Ampirik bulgular, ülkeye özgü farklılıkları ortaya koymaktadır. İlk olarak, Çin'de yeşil enerji, sürdürülebilir kalkınmayı yönlendirmektedir ve sürdürülebilir kalkınmadan yeşil teknolojiye doğru güçlü tek yönlü bir nedensellik mevcuttur. Hindistan'da ise sürdürülebilir kalkınma ve yeşil enerji birbirlerini karşılıklı olarak etkilemektedir.*

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Buna karşılık, Brezilya ve Güney Afrika'da sürdürülebilir kalkınmadan yeşil teknolojiye doğru çift yönlü bir nedensellik görülmektedir. Rusya'da da yeşil teknolojiden sürdürülebilir kalkınmaya doğru çift yönlü bir nedensellik olduğu gözlemlenmektedir. Sonuç olarak, bu çalışma yeşil dönüşümün genel sürdürülebilir kalkınmayı nasıl desteklediğine ilişkin literatürdeki kritik bir boşluğu doldurmaktadır. Elde edilen sonuçlar, politika yapıcılar için etkili uzun vadeli sürdürülebilirlik stratejileri ve önlemler konusunda pratik içgörüler sunmaktadır.

Anahtar Kelimeler: *Sürdürülebilir Kalkınma, Çevresel Sürdürülebilirlik, Yeşil Enerji, Yeşil Teknoloji, BRICS*

1. Introduction

The importance of sustainable development and economic growth as key objectives for many nations has long been recognized (Raza and Chen, 2025). In the face of environmental crises and socioeconomic vulnerabilities brought about by the Anthropocene age, sustainable development is now at the center of discussion among academics, decision-makers, policymakers, and market actors. This rising interest stems from the soaring systemic pressures caused by human activity. These pressures include climate change, loss of biodiversity, overuse of resources, and altered natural temperature regimes. Collectively, these affect the integrity and resilience of ecosystems and, in turn, the stability of the economy, social welfare, and the potential for long-term sustainable development (Assa, 2021; Hickel, 2020; Zhao and Shah, 2024). Sustainable development is a specific kind of development. It integrates economic, ecological, and social aspects while promoting the well-being of the planet and its resources (Zhang and Wu, 2022: 2; Costantini and Monni, 2007: 329). The concept of sustainable development first emerged internationally at the 1972 Stockholm Conference. The 1987 Brundtland Report outlined its main principles. The report defined it as a conceptual framework aimed at "meeting the needs of the present without compromising the ability of future generations to meet their own needs." This concept was addressed in greater detail at the 1992 Earth Summit in Rio.

Furthermore, the Rio Declaration urges all governments to create plans to preserve the environment and natural resources for future generations. Afterward, its definition was updated in 2015. The United Nations 2030 Agenda has put forward a holistic development framework consisting of the Sustainable Development Goals (SDGs). The SDGs aim to harmonize human activities within Earth's limits to sustain human existence (Zeng, Maxwell, Runting, Venter, Watson and Carrasco, 2020). This perspective has shaped a distinctive global identity for sustainable development based on the three connected pillars of social, economic, and environmental development (Hametner, 2022: 1; Pata, 2025: 2). In tandem with the 2030 agenda, SDGs have also been set to transform global ecosystems (Clark, Kavanagh, and McGeady, 2024; Gebara, Thammaraksa, Hauschild, and Laurent, 2024). Currently, the combination of green energy and green technologies is central to the world's initiatives to balance economic development and environmental sustainability (Clark et al., 2024; WCED, 1987). Sustainable development is also a key focus of international agreements such as the Paris Agreement on Climate Change (2015) and the United Nations Climate Change Conferences (COP Summits). There is also ongoing discussion about the limits of growth-focused development models (Jansen, Wang, Behrens, and Hoekstra, 2024: 696). For a long time, we have relied on concepts such as the human development index (HDI) and gross domestic product (GDP) as indicators of development. But they have been criticized for not capturing the environmental costs of growth and for not being adequate measures of sustainability (Assa, 2021; Costanza, Daly, Fioramonti, Giovannini, Kubiszewski, Mortensen, Pickett, Ragnarsdottir, De Vogli, and Wilkinson, 2016; Hickle, 2020; Hametner, 2022; Jansen et al., 2024).

Although the HDI incorporates a broader social dimension than GDP, both metrics fail to fully capture the extent to which global ecological boundaries are exceeded, nor do they adequately reflect multidimensional social progress. This limitation indicates that development can no longer be defined solely through quantitative economic growth; rather, it must be rethought within strict ecological limits and social justice frameworks (Raworth, 2017; Hickel, 2020). The "doughnut economy" model (Raworth, 2017) posits that sustainable human development is achievable only by respecting the planet's ecological ceiling. Exceeding this ceiling triggers severe adverse effects on human development, such as climate-related disasters and resource scarcity. Consequently, while current sustainability debates heavily emphasize human well-being, true human development remains unattainable without a solid foundation of ecological sustainability (Neumayer, 2010: 1-2).

UN policymakers are increasingly focusing on moving beyond GDP when measuring sustainability. GDP has long been the main metric for measuring economic growth. This view reflects UN Secretary-General António Guterres's long-standing call for a broader measure of development. As he stated, "going beyond GDP is fundamental to building an economic system that values what matters to everyone, now and in the future: human well-being" (Maigne, 2025). The goal is to create a metric that augments GDP rather than replaces it. Furthermore, it is emphasized that going beyond GDP is not merely a macroeconomic issue, but rather a matter that encompasses all dimensions and critical drivers of sustainable development, with profound implications for people, the planet, prosperity, peace, and partnerships (United Nations, 2021). Sustainable prosperity for all cannot be achieved through an economic system geared solely toward GDP-driven growth, as such a system remains structurally unsustainable (Assa, 2021: 1; Hickel, 2020: 2; Jansen et al., 2024: 697).

The multidimensional Sustainable Development Index (SDI) has been regarded as a useful metric for assessing sustainability. This paper aims to contribute to the literature by examining how the SDI -a holistic measure of sustainable development- relates to the drivers of the green transition within the framework of ecological realism. Most previous studies have relied on restricted indicators focused primarily on economic growth or environmental degradation, frequently overlooking cross-country interdependencies. To address the research purpose, panel data for the BRICS nations for the period from 1992 to 2022 were considered for analysis. The SDI, green energy, and green technology were selected as study variables. Given heterogeneity and cross-sectional dependence, the causal links among variables were explored using a bootstrap-based panel approach. The study was driven by two research questions, namely "Does the green transition really boost sustainable progress?" and "To what extent does it capture sustainability aspects that one-dimensional indices, such as the HDI, GDP, and EF, fail to measure?"

The structure of the article is as follows. The second chapter presents the literature review, while the third chapter outlines the data and methods. The fourth chapter presents the empirical findings, and the final chapter covers conclusions and policy implications.

2. Literature Review

Sustainable development acknowledges the interconnectedness of economic growth, environmental protection, and social welfare. It offers a comprehensive model for advancing social equity, facilitating economic prosperity, preserving environmental integrity, and mitigating climate change impacts (Khan, Ali, and Zhu, 2025: 1; Zhang, Wang, Adebayo, and Altuntaş, 2022: 1234). Since the mid-20th century, growing environmental problems mainly from increased economic activity and climate change have led people to question whether GDP growth should remain the main goal of economic policy. Unrestricted economic expansion has adversely affected environmental systems -particularly through escalating climate change impacts- and these consequences have grown increasingly severe. However, climate change only represents one side of a broader spectrum of environmental degradation: such challenges also encompass species extinctions, ecosystem collapse, and desertification are also issues. Additionally, the literature indicates that rapid economic expansion does not inherently reduce social inequality. Beyond a certain threshold of economic development, improvements in living conditions also tend to plateau (Ramesh, 2022: 70).

According to the Human Development Index (HDI) founder, Mahbub ul Haq, the essence of development is a long, healthy life, better education, and a decent standard of living. This does not mean development is merely a matter of improving people's lives through a faster-growing economy. Rather, it means that we must put people's well-being at the heart of development and then measure progress in terms of people's lives. In other words, people's well-being means preserving a supportive environment for both current and future generations. From this perspective, the SDI is formulated. The SDI is important on two levels. First, it indicates that an environment with both a high quality of life and low environmental pressures can exist when the right sort of policies are in place. Second, it represents a new state of measurement and understanding, an advancement that is both conceptual and methodological. It links human development, climate change, and sustainable development, a link that is not clearly established. This is crucial because these areas have traditionally been considered separately, at least by the United Nations (Togtokh and Gaffney, 2010). The framework aims to fill this gap by measuring the interactions among economic growth, human welfare, and environmental sustainability from a holistic perspective.

The IUCN's (1980) initial work, World Conservation Strategy, further stresses that humans must enhance their living standards and enjoy the benefits of economic growth and the prosperity of nature, considering the constraints imposed by natural resources and the carrying capacity of ecosystems (IUCN, 1980). From this perspective, the success of sustainable development hinges on striking a harmonious equilibrium between environmental quality, social justice, and economic expansion (Liu, Padhan, Rekha, and Gozgor, 2025). Rapid urbanization, industrial expansion, and population influx all have adverse impacts on sustainability, and it makes it more difficult to reach this equilibrium. making it increasingly difficult to reach this equilibrium. In turn, the resulting environmental threats impede the trajectory of decarbonization and compromise environmental sustainability. Hence, a growing body of studies has examined the determinants of sustainability performance.

Conversely, the UN has established a sustainability framework oriented toward the economic, social, and environmental dimensions. The main goal is to foster sustainable growth globally. Within this framework, green energy and eco-friendly technological innovations serve as primary drivers contributing to sustainable development. These transitions help boost renewable energy output and curb carbon emissions, thus facilitating advancements toward the realization of the SDGs (Yang, Wang, Dong, and Jiang, 2023). (Yang, Wang, Dong, and Jiang, 2023). Furthermore, eco-friendly technological innovations are used as instrumental in economic growth by encouraging the development of environmental patents (Liu et al., 2025).

Globally, BRICS economies are some of the fastest growing and largest consumers of global energy resources. However, despite rapid industrialization and expanding populations, their environmental sustainability competitiveness is comparatively lower than that of many other developing countries. One major reason is their dependence on nonrenewable energy sources and concerns about energy security (Wei and Huang, 2022: 759). To achieve long-term sustainable development in these countries, growth and development policies are needed that reduce an ecological footprint while increasing biological capacity (Raza and Chen, 2025). Hickel's (2020) SDI has been identified as a vital indicator linking human development, climate change, and sustainable development within the planet's ecological boundaries. Table 1 shows the SDI and its subcategories.

Table 1. SDI and Sub-Categories

Rank (163)	Country	(a)	(b)	(c)	(d)	(e)	(f)	(g)
38	Brazil	0.741	73.4	15.6	8.3	14.616	2.54	17.29
50	South Africa	0.712	61.5	14.3	11.6	13.186	6.06	6.21
53	India	0.694	67.7	12.6	6.6	6.951	1.55	5.02
109	Russian Federation	0.541	70.1	15.7	12.4	26.992	9.16	13.54
135	China	0.378	78.6	15.2	8.1	18.025	7.24	24.81

Source: https://www.sustainabledevelopmentindex.org/. (a) SDI, (b) Life Expectancy (years), (c) Expected Years of Schooling, (d) Mean Years of Schooling, (e) Income (GNI per capita constant 2017$ PPP), (f) CO_2 emissions per capita, (g) Material Footprint per capita (tonnes).

As Table 1 shows, the potential for sustainable development in the BRICS varies, with divergent trends. Brazil (0.737), ranked 38th worldwide from 163 countries, has the highest SDI value in the group. This result indicates that Brazil has reached a healthier balance between human development and environmental pressures, with relatively lower carbon intensity (2.54 tons of CO_2) and a moderate material footprint. However, both China (0.378) and Russia (0.541) have lower-than-anticipated SDI performance, considering their relatively high life expectancy and income levels. This is primarily due to China's highest material footprint (24.81 tons) and Russia's highest carbon intensity (9.16 tons of CO2). These findings back up a core assumption of SDI. In particular, the text highlights that long-term sustainable development cannot be achieved when economic growth and human development are pursued without environmental sustainability. Although both Brazil (73.4 years) and China (78.6 years) have a higher life expectancy than Russia (70.1 years), the education indicators (expected and average years of schooling) suggest that human capital accumulation is not necessarily reflected in stronger environmental performance. These findings also underscore a vital contribution of the SDI: demonstrating that human development is a necessary but insufficient condition for sustainable development. Although China ($18,025 PPP) and Russia ($26,992 PPP) have a relatively higher income per capita, both countries have lower SDI positions.

Conversely, Indian income levels (although relatively low at $6,951 becausePPP) are associated with a higher SDI score (0.694). This could be taken as evidence of the "high income-high environmental pressure paradox" discussed in the literature (Raworth, 2017: 164; Hickel and Kallis, 2020: 471). CO_2 emissions and material footprint stand out as primary determinants of SDI performance. Russia's per-capita CO_2 emissions are 9.16 tons, with a material footprint of 13.54 tons. In China, CO_2 emissions are 7.24 tons per capita, and the material footprint is 24.81 tons. These figures suggest that excessive dependence on fossil fuels, energy-intensive production, and resource-driven growth severely constrain sustainable development.

In contrast, India and Brazil perform better on the SDI mainly because their emissions are lower. In emerging countries such as the BRICS, the SDI reflects development patterns that are either conventional or increasingly resource- and carbon-efficient, driven by the adoption of green technologies and the shift to renewable energy. This move toward cleaner energy could play a strategic role in sustainable development because it is central to both *the Paris Climate Agreement* and *the 2030 Agenda for Sustainable Development*. In this regard, the mission of the SDGs and the national commitments emerging from COP summits depend heavily on transitioning to green energy and continuing progress in green technology. The SDGs strongly emphasize these issues at the center of development. A literature review identified several studies using different indicators to measure sustainable development. Table 2 summarizes these studies.

Table 2. Literature Review List

Authors	Country/Period	Method	Evidences
Khan et al. (2025)	Pakistan 1990-2023	ARDL	GI ↑ → EG ↑ (short-long run), RE at long run ↓ → EG ↓
Khan, Ali and Zhu (2025)	Ten Emerging Economies, 2004-2020	Panel MMQR	RE (Renewable Electric) ↑ and GT ↑ → EG ↑
Azam, Rafiq, Shafique, and Yuan (2023)	30 Emerging Economies 1990-2017	Panel Cointeg. Causality	GE ↑ → HDI ↑ GE ↔ HDI (bidirectional causality)
Wei ve Huang(2022)	10 Asian Economies 1990-2020	CS-ARDL	RE ↑ → ANS ↑
Güney (2020)	20 High-Income Countries 1990-2015	Panel Cointeg. Causality	RE ↑ → ANS ↑ (short-long run) RE → ANS (unidirectional causality)
Amin, Shabbir, Pan, and Asif (2025)	BRICS 1995-2022	AMG CCE-MG Causality	GI ↑, GE ↑ → CO_2 ↓ GE ↔ CO_2, GI ↔ CO_2
Li and İmran (2025)	G5 Countries 2000-2022	CS-ARDL	GT ↑ , RE ↑ → EF ↓
Zhang et al. (2024)	BRICS 1980-2017	Panel MMQR	GE ↑, TI ↑ → EF ↓ (ecologic sustainability↑)
Fang (2023)	China 2005-2019	System GMM	GI ↑, GE ↑ → CO_2 ↓
Caglar et al. (2024)	Top 10 Economies 1990-2021	CS-ARDL	GT ↑ , RE ↑ → LCF ↓
Wang, Pal, Mahalik and Gozgor (2025)	14 Developing Countries 1990-2022	Convergence	GT ↑, GE ↑ → SDGI↑
Degirmenci, Aydin, Bozatli and Ahmed (2025)	25 OECD Countries 1990-2019	CS-ARDL CS-DL	GI↑, RE ↑ → SDGI↑
Xing, Danish and B. Tolgay (2025)	33 OECD Countries 1995-20218	CCE-MG	GI↑ → SDGI↑
Islam (2025)	G7 Countries 2002-2020	Panel Quantile Regression	GI↑ → SDGI↓
Islam et al. (2022)	ASEAN Countries 1980-2018	Panel Cointeg.	RE ↑ → SDGI↑
Raza and Chen (2025)	38 OECD Countries 2000-2020	2SLS, Granger Causality	GT ↑ , CE ↑ → SDGI ↑ GT ⟶ SDGI
Behera et al. (2025)	India 1987-2020	Dynamic ARDL	GT ↑ , RE ↑ → SDGI ↑
Noor et al. (2024)	South Asian Countries 1995-2019	Panel ARDL Causality	GE ↑ , RE ↑ → SDGI ↑ RE → SDGI (unidirectional causality)
Chen, Olawunmi, Ribeiro, Khan, and Abbas (2024)	China 1990-2020	Breitung Candelon Causality	GT↑ → SDGI ↑ GT ⟶/ SDGI
Omri (2020)	75 Countries 1990-2014	Panel Cointeg.	High-income:GT ↑ → SDGI ↑ Middle-income: GT ↑ → SDGI↑ Low-icome: GT ≈ SDGI

Note: The table presents the following indicators. CE: Clean Energy, EG: Economic Growth, GT: Green Technology, GI: Green Innovation, RE: Renewable Energy SDGI: Sustainable Development Goals Index ↑, ↓, ≈ the symbols represent increase, decrease, and uncertainty, respectively. In this research, green innovation, environmental patents, and green technology investments represent green technology, whereas renewable energy and clean energy parameters represent green energy.

The findings in Table 2 vary by country (or country group), time period, and methodology. As indicated by the studies mentioned in Table 2, the existing research literature has predominantly applied one-dimensional indicators, including economic growth, human development, net national savings (NNS), and environmental indicators such as the ecological footprint, CO_2 emissions, and LCF, to measure sustainable development. Sustainable development and ecological sustainability require a multidimensional approach. However, studies that explicitly incorporate environmental dimensions into these analyses remain relatively scarce. From a policy perspective, the SDGs should be addressed through comprehensive indicators, with greater emphasis on measures beyond purely environmental ones (Değirmenci et al., 2025: 824; Pata, 2025: 2).

3. Data, Methodology, Findings

3.1. Data

In this study, we focus on the stability and direction of the nexus between sustainable development (SDI), green energy (GENERGY), and green technology (GTECH) across the BRICS countries. Using annual data from 1992 to 2022, we perform the analysis with a panel bootstrap causality approach. The study covers the BRICS nations (Brazil, Russia, India, China, and South Africa). These nations represent roughly 40% of the world's population and 26% of the world's GDP. These countries are significant contributors to global atmospheric emissions and thus play a key role in the sustainable development agenda of the 21st century. At the same time, they often face the challenge of addressing increasing demand for human development while responding to environmental pressures linked to climate change and environmental degradation. They also incur additional costs to fulfill international commitments and adapt to climate change.

The SDI proposed by Hickel (2020) is employed to evaluate the ecological efficiency of human development, on the grounds that development must take place within planetary boundaries. Each country's level of human development (life expectancy index, education index, and modified income index) is calculated according to Hickel (2020: 5-6) by dividing the index of development by the degree to which CO_2 emissions and material footprint exceed the fair share of planetary boundaries in terms of consumption. Consequently, nations that simultaneously achieve high human development and environmental performance while remaining within planetary boundaries achieve more favorable rankings. To examine the causal link between green energy and green technology, these variables were transformed into their logarithmic forms. The empirical model developed (Eq. 1) and the definitions of the variables used in the model are placed below (Table 3).

$$lnSDI_{it} = lnGENERGY_{it} + lnGTECH_{it} \quad (1)$$

Table 3. Variable Descriptions

Variables	Description	Source
SDI	Sustainable Dvelopment Index (From 0 to 1)	SDI Hickel (2020)
Green Energy	Share of electricity production from renewables (%) The source of renewables encompasses solar, wind, hydropower, bioenergy, geothermal, and ocean-based sources such as wave and tidal energy.	OurWorldinData https://ourworldindata.org/renewable-energy
Green Technology	Patents on environment technologies % of all technologies	OECD Open Data Platform

In Table 4, the mean of the lnSDIs series is negative, whereas the means of the lnGENERGY and lnGTECH series are positive. The mean and median differ by little, suggesting the data are relatively symmetrically distributed. In this model, the minimum value of the lnGENERGY variable is negative, whereas the maximum value is positive. The lnGTECH series also shows a relatively wide range between minimum and maximum values, suggesting considerable variation in the level of green technology among countries.

Table 4. Descriptive Statistics

	lnSDI	lnGENERGY	lnGTECH
Mean	-0.433264	2.649752	4.651387
Median	-0.388608	2.863289	4.440689
Maximum	-0.271809	4.558137	9.702963
Minimum	-0.972861	-2.482083	1.093041
Std. Deviation	0.140419	1.477736	1.637666
Skewness	-1.392756	-1.100803	0.894417
Kurtosis	4.825644	3.908466	3.924441
Jarque-Bera	71.63615	36.63409	26.18545
Probability	0.000000	0.000000	0.000002
Number of Observations	155	155	155

Whereas the dependent variable, lnSDI, shows the lowest variance, the larger standard deviations of the lnGTECH and lnGENERGY series indicate more variation across countries. Regarding skewness, the lnSDI and lnGENERGY series display negative skewness, whereas the lnGTECH series is positively skewed. The kurtosis values, which are above 3 for all series, suggest that the distributions include more extreme outliers. The normality test outcomes further confirm that none of the variables follow a normal distribution. Using bootstrap-based panel data methods could improve the reliability of the results. Finally, each series has 155 observations. This provides sufficient robustness for bootstrap-based causality analyses.

3.2. Methodology

3.2.1. Cross-Section Dependency (CSD) and Homogeneity Test

In panel data analysis, CSD among units may generate biased and inconsistent estimates. CSD is especially important in countries that have a common economic link, such as the developed, developing, and transition economies (Yilanci and Ozgur, 2019: 24799; Menyah et al., 2014: 39). Factors such as global economic shocks, international trade, globalization, and financial integration all help create interdependencies among countries (Menyah et al., 2014: 39). Therefore, CSD becomes an important consideration because shocks originating in one country may spread to others. Accordingly, testing for the presence of CSD is a key methodological step in analyzing the BRICS countries (Yilanci and Ozgur, 2019: 24799; Menyah et al., 2014: 39). Before the causality test, we examined possible cross-section dependence among the BRICS countries using four different cross-section dependence tests. First, we calculated the panel test statistics. In order to test CSD for the model, the Breusch and Pagan (1980) LM test statistic appropriate for the case of N > T was computed as follows (Menyah et al., 2014: 39).

$$y_{it} = \alpha_i + \beta_i x_{it} + u_{it} \quad i = 1, \ldots\ldots.., N \; ve \; t = 1, \ldots\ldots\ldots T \tag{2}$$

Here, y_{it} is the dependent variable, x_{it} and $kx1$ are the vectors of explanatory variables, and the indices i and t correspond to the panel's units and time dimension; α_i and β_i are the country-specific cross-sectional and slope coefficients, respectively. In this context, the cross-sectional independence hypothesis $H_0 : Cov\left(u_{it}, u_{jt}\right) = 0$ is tested for all t and for $i{\neq}j$. The alternative hypothesis $H_0 : Cov\left(u_{it}, u_{jt}\right) \neq 0$ is tested against at least one pair of $\neq j$.

$$LM = T \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij} \;\rightarrow d \; X^2_{\frac{N(N-1)}{2}} \tag{3}$$

The standard LM test does not work well when there are many cross-sectional units (N), especially as N approaches infinity. To solve this problem, Pesaran (2004) introduced a new LM statistic that is valid when both N (N→ ∞), and T (T→ ∞) are large (Gurdal et al., 2020: 10; Yilanci and Ozgur, 2019: 24799).

$$CD_{LM} = \sqrt{\frac{1}{N(N-1)}} \; \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} (T\hat{\rho}_{ij}^2 - 1) \tag{4}$$

Indeed, according to Pesaran (2004), when the cross-sectional dimension is larger than the time dimension (N > T), the following test statistic should be used:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \; \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \tilde{\rho}_{ij} \tag{5}$$

If the population mean has zero interpair correlations, the CD test may lose effectiveness even in the presence of nonzero correlations between individual panel units. Pesaran, Ullah, and Yamagata (2008) proposed LM_{adj}, a bias-corrected version of the LM test. This procedure is based on the full-sample mean and variance of the LM statistic under large-panel asymptotics, with T→ ∞ and then N→ ∞. The test statistic is calculated as follows (Nazlioglu, Lebe, and Kayhan, 2011: 6618).

$$LM_{adj} = \sqrt{\left(\frac{2}{N(N-1)}\right)} \; \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{(T-k)\,\hat{\rho}_{ij}^2 - \mu_{T_{ij}}}{\vartheta^2 T_{ij}} \rightarrow d \;\; N(0{,}1) \tag{6}$$

The estimated $\tilde{\rho}_{ij}$ values in all test statistics demonstrate a presence of correlation among the error terms. The null hypothesis of cross-sectional independence is tested via these procedures, as opposed to the alternative proposition of dependence among the panel members.

The delta $(\tilde{\Delta})$ test developed by Pesaran and Yamagata (2008) is derived from Swamy's (1970) slope homogeneity test. Pesaran and Yamagata (2008) scrutinized the delta $(\tilde{\Delta})$ test to check whether slope coefficients are the homogen $(H_0 : \hat{\beta}_i = \beta)$, across the whole panel or if they differ $(H_1 : \hat{\beta}_i \neq \beta)$. Under the assumption of normally distributed error terms, the delta test works as $(N, T) \rightarrow \infty$ without imposing restrictions on the relative growth rates of N and T. Because this method uses a modified version of Swamy's test, the first step is to calculate the following equation (Nazlioglu et al., 2011: 6618).

In the equation, $\hat{\beta}_i$ and $\tilde{\beta}_{WFE}$ are the pooled least squares and weighted fixed effects estimators are used. $\tilde{\sigma}_i^2$ *and* M_T are also the estimator of σ^2 and the matrix of T. In panel structures characterized by small N and large T, the Swamy test can handle cross-sectional heteroskedasticity. The test statistic for the slope coefficients can be formulated as follows:

$$\tilde{S} = \sum_{i=1}^{N} (\hat{\beta}_i - \tilde{\beta}_{WFE})' \frac{x_i' M_T x_i}{\tilde{\sigma}_i^2} (\hat{\beta}_i - \tilde{\beta}_{WFE}) \quad (7)$$

$$\tilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - k}{\sqrt{2k}}\right); \tilde{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - E(\tilde{z}_{iT})}{\sqrt{Var(\tilde{z}_{iT})}}\right) \quad (8)$$

In this formula, k stands for the number of exogenous explanatory factors. $\tilde{S}$ and N refer Swamy's test statistic and cross-sectional size, respectively. $\tilde{\Delta}$ is recommended for small samples, improving the test's performance of the $\tilde{\Delta}_{adj}$ when the errors follow a normal distribution (Ozcan and Ozturk, 2019: 34).

3.2.2. Kónya Causality Test

This section employs Kónya's (2006) panel causality framework to identify the direction of causality between the variables. The method is based on a seemingly unrelated regression (SUR) system and Wald test statistics to examine the causal relationships of each unit within a heterogeneous panel. Furthermore, Kónya's (2006) panel causality test offers a more technically robust framework than panel unit root tests and cointegration tests. This approach does not require assumptions about whether the variables are stationary. Using country-specific bootstrap critical values helps ensure reliable results, even if the series have different integration orders (Bahmani-Oskooee and Wu, 2018: 122; Kónya, 2006: 980). Unlike traditional approaches, this test does not assume homogeneity in causal relationships across all units. Beyond specifying the lag structure, the model does not rely on strict functional assumptions, which allows for more flexibility (Kónya, 2006: 980). The first step is to estimate the system of equations using Zellner's SUR method. The system for the model is as follows:

$$Y_{1,t} = \alpha_{1,1} + \sum_{l=1}^{mly_1} \beta_{1,1,l} Y_{1,t-l} + \sum_{l=1}^{mlx_1} \delta_{1,1,l} X_{1,t-1} + \varepsilon_{1,1,t} \quad (9)$$

$$Y_{2,t} = \alpha_{1,2} + \sum_{l=1}^{mly_1} \beta_{1,2,l} Y_{2,t-l} + \sum_{l=1}^{mlx_1} \delta_{1,2,l} X_{2,t-1} + \varepsilon_{1,2,t}$$

$$\cdots\cdots$$

$$Y_{N,t} = \alpha_{1,N} + \sum_{l=1}^{mly_1} \beta_{1,N,l} Y_{N,t-l} + \sum_{l=1}^{mlx_1} \delta_{1,N,l} X_{N,t-1} + \varepsilon_{1,N,t}$$

And

$$X_{1,t} = \alpha_{2,1} + \sum_{l=1}^{mly_1} \beta_{2,1,l} Y_{1,t-l} + \sum_{l=1}^{mlx_1} \delta_{2,1,l} X_{1,t-1} + \varepsilon_{2,1,t}$$

$$X_{2,t} = \alpha_{2,2} + \sum_{l=1}^{mly_1} \beta_{2,2,l} Y_{2,t-l} + \sum_{l=1}^{mlx_1} \delta_{2,2,l} X_{2,t-1} + \varepsilon_{2,2,t}$$

....

$$X_{N,t} = \alpha_{2,N} + \sum_{l=1}^{mly_1} \beta_{2,N,l} Y_{N,t-l} + \sum_{l=1}^{mlx_1} \delta_{2,N,l} X_{N,t-1} + \varepsilon_{2,N,t}$$

In these equations, Y represents sustainable development, whereas the other variables denote green energy and green technology. l symbolizes the lag length, and N, t represent the number of countries, and the time dimension, respectively. The optimal lags of the equations are selected using the Akaike or Schwarz information criteria (lag numbers between 1 and 4), as advised by Kónya (2006). In Kónya's (2006) panel causality method, each equation is for a different country, and calculations are done separately based on each country's number of observations. The same set of variables is used in all equations, but only the slope coefficients and sample characteristics can differ between countries (Kónya, 2006: 981-982).

3.3. Empirical Findings

In this empirical study, we first carried out CSD and homogeneity tests on the variables. These tests aimed to identify the relationships between the variables and their directions. We used the Kónya (2006) causality test to examine these connections. According to the CSD tests (Table 2), we accepted the alternative hypothesis that CSD exists for each specified causality equation at the 1% significance level. The slope homogeneity test produced a p-value < 0.05, confirming the hypothesis of slope heterogeneity. The results obtained are as follows.

Table 5. Cross-Section Dependency and Delta Tests

	SDI ⇏ GENERGY	GENERGY ⇏SDI	SDI ⇏ GTECH	GTECH⇏SDI
LM	103.14 (0.000)	66.58 (0.000)	130.36 (0.000)	96.81 (0.000)
CD_{LM}	20.82 (0.000)	12.65 (0.000)	26.91 (0.000)	19.41 (0.000)
CD	8.75 (0.000)	2.63 (0.004)	10.97 (0.000)	7.79 (0.000)
LM_{adj}	44.98 (0.000)	40.70 (0.000)	22.07 (0.000)	21.46 (0.000)
Δ	13.61 (0.000)	13.58 (0.000)	19.87 (0.000)	13.91 (0.000)
Δ_{adj}	14.32 (0.000)	14.29 (0.000)	20.91 (0.000)	14.64 (0.000)

Note: If $p < 0.05$, there is statistical significance at the 5% significance level

After these findings, panel bootstrap causality analysis was employed. The panel causality relationship was tested using Wald test statistics. Critical values were obtained via bootstrap methods. These were used to address biases arising from small sample sizes.

Table 6. Findings of the Causality Test Between SDI and Green Energy

	H_0: SDI ⇏ GENERGY				H_0: GENERGY ⇏SDI			
	Test Stat.	Critical Values			Test Stat.	Critical Values		
		%1	%5	%10		%1	%5	%10
Brazil	1.50	20.91	12.86	10.26	5.90	11.26	7.88	6.53
China	5.46	34.11	25.79	22.40	13.78*	22.19	15.24	13.21
India	5.78***	5.14	3.13	2.59	7.70***	7.19	5.48	4.35
Russia	0.00	4.67	2.54	1.83	0.011	3.717	2.00	1.47
South Africa	5.10	12.97	9.92	8.01	0.68	3.09	1.82	1.27

Note: Asterisks ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 6 reveals a bidirectional causality between sustainable development and green energy in India, whereas a unidirectional causality from green energy to sustainable development is observed in China. Conversely, the analysis detects no causal nexus between the two variables in Brazil, Russia, and South Africa, implying that green energy consumption does not exert a measurable effect on the SDI in these countries.

Table 7. Findings of the Causality Test Between SDI and Green Technology

	H_0: SDI ⇏ GTECH				H_0: GTECH⇏SDI			
	Test Stat.	Critical Values			Test Stat.	Critical Values		
		%1	%5	%10		%1	%5	%10
Brazil	30.04**	34.86	26.12	23.17	0.06	8.94	6.27	4.98
China	2.52***	1.88	1.23	0.87	50.94***	15.59	13.01	1.28
India	0.16	13.93	11.57	10.01	9.95*	13.45	11.01	9.63
Russia	1.61	5.00	3.41	2.60	3.93*	6.47	4.71	3.85
South Africa	2.50*	4.81	2.71	2.03	0.68	2.70	1.75	1.30

Note: Asterisks ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

The results in Table 7 indicate a strong bidirectional causality between sustainable development and green technology in China. These findings demonstrate a mutually reinforcing cycle where green technology policies (such as environmental patents) stimulate sustainable development, and vice versa. Specifically, development-focused goals drive investments and applications in green technology. In Brazil and South Africa there is a unidirectional causality from sustainable development to green technology, whereas green technology does not drive a causal effect on sustainable development. China, India, and Russia exhibit unidirectional causality from green technology to sustainable development, whereas sustainable development shows no statistically significant causal relationship with green technology. In India, investments and applications in green technology development can play a pivotal role in achieving and managing the SDGs.

Therefore, policymakers should prioritize accelerating green technological development and applications to foster sustainable development. In Russia, green technology-focused sustainability policies serve as an effective tool for achieving this balance, although development-oriented goals do not reciprocally stimulate green investments. In South Africa, although the SDI level motivates green technological development, the reverse relationship does not hold. This suggests that the influence of green technology incentives on SDI performance has not yet fully materialized, implying that current regulatory frameworks may still fall short of achieving their intended environmental outcomes.

4. Conclusion and Policy Implications

Research findings reveal that the use of green technology and green energy in BRICS economies operates as a vital determinant in combating environmental pressures and achieving sustainable development goals. This case will enhance the sustainability potential of development by achieving human and planetary well-being free from negative environmental effects. When examining the causal relationships between

SDI (with HDI and ANS as proxies for sustainable development) and GE, the bidirectional causality result for India echoes the bidirectional causality outcome reported by Azam et al. (2023) between GE and HDI. The study finds unidirectional causality from green energy to the SDI in China. This differs from Azam et al. (2023)'s result. Likewise, Noor et al. (2024)'s evidence of unidirectional causality from RE to SDI aligns with the unidirectional causality from GE to SDI found for China. Together, these results indicate that progress in green energy can contribute to sustainable development. In a related vein, Güney (2000)'s finding of unidirectional causality from RE to ANS likewise supports, within this same framework, a unidirectional causality between renewable energy and indicators of sustainable development. However, the results also make it clear that the direction of causality may differ across countries depending on the specific indicator being considered.

When assessed using GTECH/GI/GT, the unidirectional causality from GT to SDI in China matches the unidirectional causality from GT to SDI reported by Raza and Chen (2025). In addition, Amin et al. (2025) found bidirectional causality between GI and CO_2, suggesting that even though the variables are not identical, green innovation may interact with environmental and sustainability-related indicators. Although Brazil and South Africa show a unidirectional causal relationship from SDI to GTECH, India and Russia display the opposite pattern (unidirectional causality from GTECH to SDI), implying that causality runs in the reverse direction in these countries. This direction is consistent with the unidirectional causality from GT to SDI reported by Raza and Chen (2025). Moreover, the causality results broadly align with ARDL and regression findings that analyze the links between green technology, green energy, and sustainable development. Wang et al. (2025), Değirmenci et al. (2025), Islam et al. (2022), Omri (2020), Behera et al. (2025), and Xing et al. (2025) all show that green technology and/or green energy have a positive effect on sustainable development. By contrast, Islam (2025) finds that green technology has a negative impact on sustainable development, which departs from studies that largely report positive effects. Overall, the causality evidence continues to support the positive impact emphasized throughout the literature.

From panel units, China indicates that the bidirectional causal relationship between sustainable development and green technology has entered a reinforcing cycle. Indeed, clean energy production through green technologies limits environmental pollution. Furthermore, it is recommended to increase the share of research and development budgets. Also, to support technological innovation initiatives to enable more effective use of environmental technologies, investments in energy-efficient technologies, including electric vehicles, wind and solar power plants, and smart grids, should be actively promoted. National policies should focus on enhancing the impact of green technology, not on the environment but on social welfare, with particular emphasis on market-based incentives. In China, the causal relationship between green energy and sustainable development is unidirectional. These findings outline a framework consistent with central planning, target-based renewable energy investments, and carbon neutrality commitments.

Mandatory renewable energy quotas, government-backed support for green technology, and green tax mechanisms are considered important for achieving carbon neutrality targets. Specifically, although BRICS countries account for approximately half of total renewable capacity production, China produces the majority of this share. In 2023, solar power plant capacity matched the total installed worldwide in 2022. In

2024, solar and wind energy installations increased to record levels. China's wind energy capacity increased by 66% compared to the previous year, which experienced the largest growth in renewable energy capacity worldwide. These developments also support the goals of the SDGs and COP summits by reducing carbon emissions and mitigating climate-related damages. For India, green energy generation is a significant driver of sustainable development. Higher levels of sustainable development, in turn, encourage further green energy production, creating a reinforcing cycle. However, the effect of green technology on the SDI is unidirectional. Furthermore, improvements in SDI do not stimulate green technology investments. This asymmetry means that progress in SDI alone is insufficient to expand renewable energy-based production capacity.

Empirical evidence from India indicates that electricity generation from green energy sources contributes positively to SDI. Moreover, higher levels of sustainable development are found to encourage additional green energy production, suggesting a process at the individual level. However, the influence of green technology on SDI is confined to a one-way relationship. The results for India show that electricity generation from green energy sources positively affects SDI. Increases in SDI support further growth in green energy production. However, the effect of green technology on the SDI remains unidirectional. The lack of causal links between SDI and green energy in Brazil, Russia, and South Africa may stem from green energy's inability to replace fossil fuels. This inability to replace fossil fuels indicates a high dependence on fossil fuel revenues. Moreover, structural obstacles and inefficiencies in the energy sector also prevent a measurable effect on SDI. As a concrete step, fossil fuel subsidies should be gradually reduced, and the saved funds should be pivoted to green energy projects. Although unidirectional causality from green technology to SDI exists in Russia, a measurable effect of green energy on SDI has not yet been achieved. In Brazil and South Africa, unidirectional causality from SDI to green technology has been obtained. However, neither green energy nor green technology yet demonstrates a causality that would boost SDI. To address this, Brazil must leverage its existing biocapacity advantages to shrink its ecological footprint while structuring its green transition to stimulate SDI growth. Parallel to these efforts, Brazil has recently achieved record-breaking increases in renewable energy capacity. This is due to Brazil's intensive clean energy production from renewable sources, particularly hydroelectric power plants. Despite this milestone, emissions continue because the structural dependency on fossil fuels remains deeply entrenched in the transportation and industrial sectors. Furthermore, systemic pressures such as deforestation and agricultural expansion continue to undermine environmental sustainability and overall SDI performance. Meanwhile, South Africa should encourage public and private sector investments to expand green energy production, drive transformative impact on the SDI, and adopt stricter environmental regulations.

In summary, rapid population growth and economic expansion in BRICS economies are profoundly reshaping domestic energy demand. Therefore, these nations continue to heavily lean on fossil fuels to satisfy rising energy requirements. For this reason, the transition to renewable clean energy has become unavoidable for these countries to safeguard energy security and mitigate ecological risks. In addition, there are often overlooked economic and environmental costs tied to producing and using conventional, non-renewable energy sources. Because of this, these conventional sources continue to cost more overall than investments in green energy and clean technologies. To capture this paradigm and amplify the multiplier effect of sustainable growth on the SDI, positioning green technology and green energy at the center of policymaking, particularly in line with SDGs 7 and 13, remains vital. Although empirical findings show that the effects of green transformation on SDI vary from one country to another, differences across countries in how quickly the green transition progresses also influence their SDI scores. They shed light on common problems across the BRICS block. Accordingly, green transition policies should not be uniform but rather tailored to the specific institutional and socioeconomic conditions of each nation.

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