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Net-Zero Emissions Pathways in BRICS Economies: The Impact of Environmental Innovations, Policy, and Human Capital on Carbon Footprint Reduction

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ABSTRACT

The present study investigates the interconnection between environmental technology and policy frameworks in the context of pollution mitigation, focusing specifically on the BRICS economies since 1994 until 2021. Their detrimental impacts and the congruence of remedial measures with Sustainable Development Goals (SDGs) emphasize the need of addressing global environmental contaminants promptly. In addition, the very ambitious decarbonization goals of the Paris Accord have generated discussions concerning the sufficiency of existing environmental policies in stimulating essential technical advancements by 2030. By utilizing sophisticated econometric techniques such as CS-ARDL and AMG, this work offers reliable long-term estimations. Findings demonstrate that environmentally friendly technology are highly effective in reducing pollution levels. Additional evidence indicates that strict environmental regulations, together with the use of renewable energy and the improvement of human skills through education, are crucial for decreasing carbon footprint. In conclusion, the study provides policy suggestions to enhance these endeavours, therefore making a valuable contribution to wider environmental sustainability objectives.

Keywords: Carbon-Footprint, Environmental Innovations, Environmental Policy, Human Capital
JEL Classifications: Q54, O33, Q58, I25

1. INTRODUCTION

The (World Bank, 2021) assessment identifies the BRICS nations, comprising Brazil, Russia, India, China, and South Africa, as significant emerging economies that together account for more than 20% of the global economy. Over the previous decade, these countries have attained substantial economic expansion. According to statistics from the New Development Bank (NDB), the BRICS countries grew their proportion of the world Gross Domestic Product (GDP) from 11% in 2005 to around 22% in 2016. Currently, their economic growth, computed using purchasing power parity, exceeds that of the Group of Seven (G7) countries. Rapid modernization and substantial GDP and population growth continue to propel these countries to play a crucial role in the global economy. Therefore, it is unavoidable that there will be a rise in energy consumption among the BRICS member countries. Approximately 40% of the world's energy consumption and a considerable proportion of global CO_2 emissions are attributed to these countries, which accounted for 41% of the world's carbon emissions in 2017. This makes them noteworthy contributors to global carbon dioxide emissions (Ren et al., 2020; Li et al., 2022; Danish and Wang, 2019).

The current spike in greenhouse gas emissions has introduced a significant challenge to global warming, underscoring the urgent requirement for mitigations in global emissions policies (Shang and Luo, 2021). In light of increasing environmental concerns, the focus on green technologies has become of utmost importance in attaining sustainable development. The BRICS countries, which include some of the fastest-growing and largest economies in the world, have significant environmental challenges, particularly with China being the main contributor to carbon emissions (Zhao et al., 2023). Adopting green technologies in these countries is a promising opportunity to reduce their ecological footprints, promote sustainable economic development, and alleviate the effects of climate change. Nevertheless, it is crucial to have a thorough command of the correlation between green technologies and ecological footprints in order to make well-informed policy decisions (Sharif et al., 2022; Saqib et al., 2023a).

The primary objective of this research paper is to investigate the impact of green technology on the ecological footprints of the BRICS countries. The objective of this study is to analyze data on the adoption of green technologies and ecological footprint measurements in order to understand the possible contribution of these technologies in promoting sustainable development. Significantly, the BRICS economies accounted to 43.3% of the total global carbon dioxide (CO_2) emissions in 2020 (Li et al., 2022). China, with 28.81% of this amount, was the largest emitter worldwide, followed by India at 7.30% (British Petroleum Report).

By enabling sustainable growth and mitigating harmful environmental effects, green technologies play a crucial role in improving environmental sustainability. The association between conventional energy sources such as fossil fuels and climate change, air pollution, and other environmental concerns has been established (Yang et al., 2021). Green technologies, in contrast, strive to reduce the environmental impact of economic operations while fostering sustainable development (Saqib et al., 2024, Dar et al., 2022). In addition to renewable energy sources such as solar, wind, and hydropower, energy-efficient buildings and appliances, and sustainable transportation systems, these technologies comprise a wide range of innovative and sustainable solutions. These technologies have the capacity to greatly decrease CO_2 emissions, control air and water pollution, and mitigate other negative environmental effects linked to economic growth (Feng et al., 2021; Saqib and Usman, 2023).

Furthermore, the implementation of green technology has the potential to create fresh economic prospects and employment opportunities, especially in the renewable energy industry, which has experienced substantial expansion in recent times. This industry presents novel employment opportunities in the fields of wind turbine maintenance, solar panel production, and sustainable agriculture, among other areas. Prior research has investigated the factors that contribute to carbon emissions, such as green growth, technological progress, and renewable energy (Saqib, 2022a; Sarkodie, 2021; Yu et al. 2022, Khan et al. 2022), as well as the effectiveness of strict environmental regulations in improving environmental conditions worldwide (Galeotti et al., 2020).

Recent studies have examined the efficacy of environmental policies, renewable energy, and public-private collaborations, namely within the context of the environmental Kuznets curve (EKC) theory. This hypothesis now incorporates an emphasis on the influence of the level of strictness in environmental policies (Yang et al., 2022; Saqib et al., 2022a). Rigorous environmental regulations, such as imposing environmental levies on energy and transportation, have become increasingly essential as countries want to promote the generation and use of renewable energy to reduce the negative impacts of climate change and guarantee environmental sustainability (Mahmood et al., 2021). The objective of this study is to clarify the relationship between CO_2 emissions and the strictness of environmental regulations in highly polluted countries. Additionally, it seeks to investigate the contribution of renewable energy and human capital in advancing sustainable development and mitigating environmental consequences.

The present study makes numerous unique contributions to the scholarly discourse. Historically, studies have analysed the impact of technological advancement, environmental policy, renewable energy, and human capital on environmental quality at a large scale. Nevertheless, not all technical advancements are directly related to renewable energy or environmental issues. Therefore, a generic evaluation of the influence of technology may be unsuitable. The primary objective of this study is to examine the impact of environment-related domestic inventions as a percentage in all technologies (ETEC) and environmental policy (EPOL) on energy and environmental issues. Implementing a more accurate and customized methodology enables a thorough examination of progress in renewable energy and environmental sustainability. Significantly, the current body of literature badly lacks a thorough empirical investigation of the influence that ETEC and EPOL have on environmental quality. The objective of this study is to fill this void by offering valuable insights into the precise impacts of ETEC and EPOL developments on environmental quality, therefore enhancing the current academic framework.

2. LITERATURE REVIEW

The literature review of this study is organized into four separate subsections, each dedicated to examining various topics that are pertinent to the focus of the research. The first subsection analyses the correlation between environmental technologies and carbon footprints, investigating the ways in which technological interventions can impact ecological footprints. The second subsection examines the interaction between environmental policies and carbon footprints, thoroughly evaluating the influence of legislative and policy frameworks on carbon footprints. The third subsection examines the influence of renewable energy use on carbon footprints, evaluating the potential of transitioning to renewable resources to reduce carbon emissions. Lastly, the fourth paragraph assesses the impact of educational spending on carbon footprints, taking into account the function of education in promoting environmental consciousness and decreasing carbon footprints.

2.1. Nexus between Environmental Technology and Carbon Footprint

Within the present discussion on climate change mitigation, the effect of environmental technology (ETEC) on carbon footprints is crucial but ambiguous. The shift to renewable energy is widely recognized as a vital approach for mitigating worldwide carbon dioxide emissions, especially as nations negotiate the intricacies of the fourth industrial revolution. ETEC is widely recognized as a crucial element in attaining sustainable development and promoting the utilization of alternative energy sources. Nevertheless, there is ongoing debate over the precise influence of these technologies on the quality of the environment (Huo et al., 2023). Empirical evidence indicates that progress in green technology can slow down the increase of carbon emissions attributable to technological impacts. The objective of this subsection is to consolidate current information in order to elucidate the impact of ETEC on carbon footprints.

An analysis conducted by (Saqib and Dinca, 2023) investigated the impact of energy innovation on the ecological footprint in emerging economies and the he study found that energy innovations play a crucial role in reducing ecological footprints and supports the need for stronger energy regulations. According to Sharif et al. (2022), their analysis of the G7 countries revealed that the implementation of green technical advancements significantly reduces CO_2 emissions. Additionally, they showed that social globalization can attenuate the correlation between economic expansion and carbon emissions. In their study, Hussain and Dogan (2021) examined the immediate and prolonged consequences of ETEC on the carbon footprint in BRICS countries between 1992 and 2016. Their findings revealed a detrimental influence of ETEC on CO_2 emissions. Consequently, they propose that local investments in ETEC should be promoted as a means to mitigate the environmental impacts. Conversely, Milindi and Inglesi-Lotz (2023) reported contradictory results, showing that, with the exception of the construction industry, the implementation of environmentally friendly technology typically led to higher carbon footprints in different sectors across 45 nations. Furthermore, Liu et al. (2023) evaluated the influence of technical progress in China between 1997 and 2020 and discovered inconclusive findings; whereas progress in green technology sometimes led to higher carbon footprints as a result of economies of scale, they generally decreased emissions through technological breakthroughs. Furthermore, Huo et al. (2023) examined the impact of environmental technologies on the ecological footprint in China between 1991 and 2017 by employing the panel ARDL model and suggested that environmental technologies could worsen China's environmental condition, revealing the intricate nature of ETEC's contribution to environmental sustainability.

This compilation of research highlights the intricate and sometimes conflicting impacts of environmental technologies on carbon emissions, emphasizing the requirement of a discerning comprehension of ETEC's capacities and constraints within the wider context of sustainable development.

2.2. Nexus between Environmental Policy and Carbon Footprint

The empirical research emphasizes the importance of environmental policy and democratic governance in improving the condition of the environment. The democratic freedoms, stable institutions, and civil liberties serve as catalysts for individuals and organizations to voice their environmental concerns and advocate for legislative reforms that aim to attain sustainability objectives. Nevertheless, the relationship between environmental policy (EPOL) and carbon footprint is still a subject of debate, since research have yielded inconclusive findings. The differing results may be attributed to the approaches employed to quantify democracy and evaluate the environmental performance of democratic governments (Weimin et al., 2022) by suggesting to employ innovation shocks as substitutes for expected productivity (EPOL) in order to assess its influence with greater precision. (Abbas et al., 2024) emphasize the intricate dual correlation between environmental policy (EPOL) and carbon emissions, pointing out that heightened that green patents may theoretically lead to a decline the in CO_2 emissions and promote environmental sustainability. The effects of institutional policies on environmental pollution in BRICS countries are investigated by Hussain and Dogan (2021) using the Kuznets curve theoretical framework. Their results indicate that implementation of efficient environmental practices can significantly reduce ecological footprints. They recommend improving institutional quality and investing in environmental technologies to promote sustainability.

Subsequent investigations corroborate these results. The study by (Saqib and Shahzad, 2024) investigates the impact of environmental regulation and democracy on the reduction of the ecological footprint in resource abundant countries. The findings indicate that both aspects have a significant influence in environmental mitigation. A considerable negative association is shown by Danish et al. (2019) in their analysis of the influence of government conduct on CO_2 emissions in BRICS countries. In contrast, Povitkina (2018) contends that democracy provides only restricted advantages for climate mitigation, particularly in situations where corruption weakens the effectiveness of the government. Their findings indicate that the increase in global prices for exported goods has a substantial effect on CO_2 emissions in democratic countries, but has minimal impact in autocratic countries. In their study, (Acheampong et al., 2022) examine the impact of democracy on environmental quality in 46 sub-Saharan African countries. Their findings indicate a positive correlation between higher levels of democracy and increasing CO_2 emissions, especially in West Africa. However, the results of this correlation demonstrate regional variations. Finally, Farzanegan and Markwardt (2018) examine the correlation between democracy and greenhouse gasses (GHGs) in 17 MENA nations between 1980 and 2995. They find that while enhanced political participation (EPOL) does not impact global CO_2 levels, it can help to reduce local emissions. This research comprehensively demonstrates the intricate and sometimes conflicting impacts of democracy and environmental policy on carbon emissions, underscoring the importance of customized policy strategies to successfully address environmental complexities.

2.3. Nexus between Renewable Energy Consumption and Carbon Footprint

Considerable section has concentrated on the relationship between renewable energy (REC) and carbon footprints, producing diverse findings. One significant area of disagreement is the renewable energy's incapacity to fully supplant fossil fuels, which continue to be essential energy sources despite the incentives for energy efficiency (Herring, 2004). Saqib (2022b) evaluated the influence of renewable energy on greenhouse gas emissions in Asian emerging economies by employing a panel methodology. The results demonstrate that renewable energy plays a crucial role in substantially decreasing carbon footprints. Saqib et al. (2023b) advance this analysis; the former posits that the integration of renewable energy with novel technologies reduces carbon footprints, while the latter employs the CS-ARDL model to illustrate that renewable energy mitigates pollution and carbon emissions, thereby improving environmental quality in European nations.

In their study, Weimin et al. (2021) expanded the analysis to include 46 emerging countries since 1999 to 2018. They used panel-modified ordinary least squares (OLS) and dynamic panel approaches to determine that renewable energy enhances ecological quality by reducing carbon footprint. A study conducted by Hasanov et al. (2021) investigated the collective impact of technological progress, use of renewable energy, and international commerce on carbon footprints in BRICS countries between 1990 and 2017. Their conclusive findings validate that both technological advancement and the use of renewable energy can decrease CO2 footprints. In a similar vein, Akram et al. (2020) found that renewable energy is essential in reducing carbon footprints across BRICS countries, even if they observed uneven impacts caused by geographical differentiation between 1990 and 2014. The influence of renewable energy on carbon emissions in Sub-Saharan countries from 1980 to 2015 was examined by Adams and Acheampong (2019). Their study revealed substantial decreases in emissions that can be attributable to renewable energy, as verified using instrumental variable GMM analysis. The study conducted by Özbuğday and Erbas (2015) shown that energy efficiency and renewable energy have a substantial long-term impact in reducing CO2 emissions across 36 countries throughout the period of 1971-2009.

Nevertheless, not all results indicate agreement with these conclusions. The study conducted by Altin (2024) examined the influence of renewable energy on carbon emissions in G7 countries throughout the period of 1971-2023. Surprisingly, the study revealed a positive association between higher energy consumption and carbon footprints, which contradicted initial predictions. In the study (Bilgili et al., 2016) of 17 OECD countries, proposed a multifaceted relationship, observing a sustained positive correlation between the consumption of renewable energy and carbon footprints. This correlation may be attributed to the heightened carbon footprints during the manufacturing and distribution phases of renewable energy, which could potentially facilitate economic growth and, as a result, lead to an increased demand for energy. These studies together elucidate the intricate and occasionally conflicting impacts of renewable energy on carbon footprints, underscoring the intricate dynamics associated with the shift towards more environmentally friendly energy sources.

2.4. Nexus between Human Capital and Carbon Footprint

Empirical research underscores the significant role of human capital (EDU) in reducing carbon footprints, suggesting that an educated and skilled workforce can simultaneously enhance GDP and improve environmental quality. Ahmed et al. (2021) highlight that increased environmental awareness driven by human capital leads to pro-environmental behaviours such as energy conservation and recycling. Furthermore, (Saqib et al., 2022a) argue that human capital contributes to more efficient utilization of natural resources in MINT countries. Zafar et al. (2019) suggest that nations equipped with educated human capital are more likely to adopt sustainable methods for natural resource exploration and reduce energy insecurity. Additionally, human capital is instrumental in facilitating the adoption of technologies that are both environmentally friendly and energy-efficient (Feng et al., 2024).

3. DATA AND METHODOLOGICAL FRAMEWORK

3.1. Data Sources

This study utilized panel data that included the BRICS economies, which are known for their substantial carbon footprints, covering the period from 1993 to 2021. The carbon footprint (COF) estimates were obtained from the Global Footprint Network (GFPN), a comprehensive source of emission measures. Furthermore, data on environmental technology (ETEC), environmental policy stringency index (EPOL), and renewable energy consumption (REC) were obtained from the OECD database. The human capital (EDU), which include the number of years of schooling and the return on educational investments, were imported from the Penn World Table (PWT) to clarify the educational accomplishments and their economic consequences. The variables utilized in this study are presented in Table 1, which emphasizes the reputable sources recognized for their precision and dependability. This serves to strengthen the strength and credibility of the research results.

3.2. Economic Modelling

Model-1:

Carbon footprint = f (Environmental technology, Environmental Policy, Renewable energy consumption and education expenditure)

$$COF_{it} = f\,(ETEC_{it}, EPOl_{it}, REC_{it}\, EDU_{it}) \tag{1}$$

Table 2, lists the descriptive data in brief, the mean value of COF, ETEC, EPOL, REC and EDU are 3.1230, 9.3752, 2.1105, 11.6978 and 1.0529 respectively. While the Standard deviation of the COF, ETEC, EPOL, REC and EDU are 0.7964, 1.9614, 1.3885, 1.2527 and 0.3921 respectively.

3.3. Methodology

Before conducting panel data co-integration and stationarity tests, the Cross-sectional Dependence (CSD) test is applied to minimize the risk of misleading or incorrect results (Pesaran, 2021). This study employs CSD test, as formulated in equation 2.

$$CSD = \sqrt{\frac{2X}{Y(Y-1)}}\left[\sum_{i=1}^{m-1}\sum_{k=i+1}^{m}\widehat{\phi_{ik}}\hat{\phi}_{ik}\right] \tag{2}$$

Traditional unit root tests can lead to erroneous conclusions by assuming cross-section independence in models (Pesaran, 2007;

Table 1: Data variables and sources

Parameters	Symbol	Metrics	Resources
Carbon footprint	COF	Carbon footprint (metric tons)	GFN
Environmental technology	ETEC	Environment-related domestic inventions as a percentage in all technologies	OECD
Environmental Policy Stringency index	EPOL	EPS Index.	OECD
Renewable-energy Consumption	REC	Total, % of primary energy supply	OECD
Human Capital	EDU	School year and return to education	PWT

Table 2: Descriptive statistics

Variables	Mean	Min.	Max.	Standard Deviation
COF	3.1230	1.3628	3.9620	0.7964
ETEC	9.3752	7.3614	13.2585	1.9614
EPOL	2.1105	0.1134	2.9641	1.3885
REC	11.6978	9.0012	15.6341	1.2527
EDU	1.0529	0.0241	1.9561	0.3921

Source: Authors' Calculation

Pesaran, 2021). Both the CIPS and CADF tests account for cross-sectional dependence, as demonstrated in equations 3 and 4.

$$CIPS = \frac{1}{T}\sum_{i=1}^{T} j_i(T,N) \tag{3}$$

$$\widehat{CASIPS} = \frac{1}{T}\sum_{i=1}^{n} CADF_i \tag{4}$$

This research also employed cointegration tests Westerlund (2007) to explore long-run relationships between series, using his method that accommodates slope heterogeneity and cross-sectional dependence. The method, detailed in equations 5, 6, 7, and 8, utilizes two group statistics (Gt and Ga) and two panel statistics (Pt and Pa).

$$G\tau = \frac{1}{N}\sum_{i=1}^{N}\frac{\hat{\alpha}i}{SE(\hat{\alpha}i)} \tag{5}$$

$$G\alpha = \frac{1}{N}\sum_{i=1}^{N}\frac{T\hat{\alpha}i}{\hat{\alpha}i(1)} \tag{6}$$

$$\mathrm{P\tau} = \frac{\hat{\alpha}\mathrm{i}}{\mathrm{SE}(\propto \mathrm{i})} \tag{7}$$

$$\mathrm{P\alpha} = \mathrm{T}\hat{\alpha} \tag{8}$$

To address cross-sectional dependence (CD), the study utilizes the Cross-Sectionally Autoregressive Distributed Lag model (CS-ARDL). Chudik and Pesaran (2015) suggest incorporating cross-sectional averages of regressors as additional lags in the ARDL model. Long-run coefficients for the CS-ARDL can be calculated as shown in equation 9.

$$\hat{\vartheta}_{CS-ARDL,ij} = \frac{\sum_{j=0}^{q}\hat{\varnothing}_{ij}}{1-\sum_{j=1}^{p}\widehat{\delta_{ij}}} \tag{9}$$

Additionally, this study employs the Augmented Mean Group (AMG) test, developed by Eberhardt and Bond (2009), for robustness testing. The AMG method effectively handles cross-sectional dependence, non-stationarity, endogeneity, and slope variability in longitudinal data. The implications of AMG is expressed in equation 10.

$$\hat{\beta}_{AMG} = N^{-1}\sum_{i=1}^{N}\hat{\beta}_i \tag{10}$$

4. RESULTS AND DISCUSSION

Results of the cross-sectional dependency (CSD) test for the study's variables are presented in Table 3. The tests used include the Breusch-Pagan LM test, Pesaran scaled LM, Bias-corrected scaled LM, and Pesaran CSD. All tests demonstrated substantial corrected standard deviation, with p-values consistently at 0.000, so firmly denying the null hypothesis of no CSD. The observed correlation among the variables, including the interaction term, is significant and should be taken into account during data analysis to strengthen the reliability and validity of the results.

The results of stationarity tests for the variables using Cross-Sectionally Augmented IPS (CIPS) and Cross-Sectionally Augmented Dickey-Fuller (CADF) statistics are shown in Table 4. The results of these tests provide evidence that all variables exhibit stationarity at the first difference (I(1)) level, therefore effectively denying the null hypothesis of a unit root. In the analysis, this information enables dependable estimation of long-run cointegration and elasticity.

The results of the Westerlund cointegration test are shown in Table 5. The test statistics (Gτ, Gα, Pτ, Pα) include negative values, indicating a cointegrating relationship among the variables. Z-values specify the number of standard deviations by which the statistics differ from zero. The rejection of the null hypothesis of no cointegration.

Table 6 displays the outcomes of a CS-ARDL analysis intended to explore the short- and long-term dynamic interactions among key variables, providing estimated coefficients for ETC, EPOL, REC, and EDU. The short-term coefficient for ETEC stands at −0.627, showing a negative correlation with a modest significance level of 0.112. In contrast, the long-term coefficient for ETEC is −0.852, highlighting a robustly significant and negative relationship over time ($p < 0.01$). Notably, these outcomes align with prior studies conducted by (Sharif et al., 2022).

The other variables (EPOL, REC, EDU) also manifest negative coefficients in both the short- and long-term, reflecting inverse

Table 3: Cross-sectional dependence tests results

Variables	Breusch-Pagan LM		Pesaran scaled LM		Bias-corrected scaled LM		Pesaran CSD	
	Stat.	Prob.	Stat.	Prob.	Stat.	Prob.	Stat.	Prob.
COF	362.255*	0.000	48.200*	0.000	44.742*	0.000	13.885*	0.000
ETEC	196.411*	0.000	25.982*	0.000	21.285*	0.000	12.287*	0.002
EPOL	352.851*	0.000	51.854*	0.000	39.741*	0.000	10.432*	0.000
REC	312.199*	0.000	36.885*	0.000	26.288*	0.000	9.885*	0.000
EDU	298.985*	0.000	54.191*	0.000	43.741*	0.000	15.857*	0.000

*Designates the significance level at 1%, Source: Authors' estimation

Table 4: Unit root test results

Variables	CIPS		CADF	
	I (0)	I (1)	I (0)	I (1)
COF	−2.965	−5.552*	−3.850	−4.391*
ETEC	−4.852	−6.187*	−5.827	−6.822*
EPOL	−2.220	−3.521*	−3.417	−6.748*
REC	−2.274	−3.631*	−3.732	−6.428*
EDU	−2.121	−3.662*	−2.200	−3.214*

*P<0.01, Source: Author Estimation

Table 5: Westerlund cointegration test

Statistics	Values	Z-values	P-values
Gτ	−5.726*	−4.123	0.000
Gα	−12.125*	−3.105	0.004
Pτ	−15.741*	−4.514	0.000
Pα	−15.441*	−3.522	0.000

*P<0.01, Source: Author Estimation

Table 6: Findings of CS-ARDL test

Variables	Short-run		Long-run	
	Coeff.	Prob.	Coeff.	Prob.
ETEC	−0.627**	0.112	−0.852*	0.000
EPOL	−0.034**	0.010	−0.005*	0.003
REC	−0.069**	0.011	−0.129*	0.006
EDU	−0.164**	0.009	−0.668*	0.0005
ECM (−1)	−0.410*	0.000	-	-

*P<0.01, **P<0.05, Source: Author Estimation

Table 7: AMG test results

Variables	AMG	
	Coeff.	Prob.
ETEC	−0.0841*	0.0010
EPOL	−0.0408*	0.0030
REC	−0.8512*	0.0000
EDU	−0.5123*	0.0091
Constant	2.3971*	0.000

*P<0.01 and **P<0.05, Source: Author Estimation

relationships with varying degrees of statistical significance. EPOL's short-run coefficient is −0.034 ($P < 0.05$), and the long-term coefficient is even smaller at −0.005 ($P < 0.01$), suggesting persistence of the negative relationship. REC and EDU show similar patterns, with coefficients of -0.129 ($P < 0.05$) and −0.668 ($P < 0.01$) in the long run, indicating strong negative trends over extended periods. Renewable energy sources, characterized by zero CFP emissions during electricity generation, present an attractive option for mitigating emissions. Furthermore, the adoption of low-carbon transportation systems, such as public transport and electric vehicles, holds considerable potential for curtailing emissions stemming from the transportation sector, a significant contributor to CFP (Qing et al., 2022).

Furthermore, a 1% increase in renewable energy is reduced 0.129% carbon footprints and also in human capital, as measured by education, is found to significantly reduce Carbon Footprint by 0.668% in the long-term. There are several facets to the beneficial and negative effects of COF on human development. However, our results are consistent with those reached by (Sezgin et al., 2021), who assert that human development plays a vital role in fostering sustainable practices that mitigate COF. These practices include investments in renewable energy sources, the adoption of sustainable transportation systems, the implementation of energy-efficient technologies, and the enhancement of climate change awareness and education. Conversely, as living standards improve, there tends to be a corresponding increase in energy consumption, thereby leading to higher carbon footprint (Wang et al., 2023).

The robustness of the CS-ARDL method was assessed by employing the AMG approach. The long-term estimates obtained from the AMG and CS-ARDL methods exhibit consistent outcomes, indicating their comparability in most dimensions as shown in Table 7. Short-term and long-term relationships between variables were investigated using the CS-ARDL approach, and the AMG method was used to assess the validity of the results.

5. CONCLUSION AND POLICY RECOMMENDATIONS

The analysis of the BRICS economies between 1994 and 2021 uncovers a notable interaction among environmentally friendly technologies, strict environmental regulations, renewable energy, and human capital in mitigating carbon emissions. Empirical evidence emphasizes that progress in eco-friendly technology is crucial in reducing rates of pollution. Furthermore, the implementation of strict environmental rules, together with the growing use of renewable energy and a highly educated workforce, significantly contribute to the decrease of carbon footprint. This study validates the effectiveness of these combined methods in attaining more sustainable environmental results. As governments strive to achieve the decarbonization goals specified in the Paris Accord, the results emphasize the crucial importance of policy and technology in guiding these economies towards a sustainable trajectory.

It is recommended that governments augment their financial support for the study and development of environmentally friendly technologies by means of grants, subsidies, and tax incentives.

The implementation of more stringent regulations regarding the environment and the allocation of resources towards renewable energy infrastructure might stimulate innovation. It is imperative to allocate resources towards education and training initiatives that prioritize environmental sustainability in order to impart sustainability concepts to future generations. By enhancing the accessibility and cost-effectiveness of renewable energy compared to conventional fossil fuels, its adoption can be expedited.

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