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Mitigating Trade-Related CO_2 Emissions: The Role of Renewable Energy, Environmental Technologies, and Policy Stringency in BRICS Countries: A PMG-ARDL Analysis

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ABSTRACT

Trade plays a pivotal role in the economic growth and development of BRICS countries, yet it also significantly contributes to CO_2 emissions and environmental degradation. This study aims to investigate the effectiveness of renewable energy, environmentally-related technologies, and environmental policy stringency in mitigating the detrimental effects of trade on CO_2 emissions within the BRICS countries from 2000 to 2020. Utilizing panel data and the PMG-ARDL approach, we examine the long-term and short-term impacts of industrial value-added, trade, population, renewable energy, non-renewable energy, environmental-related technology, policy stringency, and geopolitical risk on CO_2 emissions. Our findings reveal that, in the long term, industrial growth, population growth, trade, and non-renewable energy consumption exert a significant and positive influence on CO_2 emissions. Conversely, renewable energy, environment-related technologies, and geopolitical risk play a significant and negative impact on emissions. Crucially, our results highlight that renewable energy and environment-related technologies effectively mitigate the adverse effects of trade on pollution. In contrast, the interaction between trade and environmental policy stringency exhibits no statistically significant impact. These findings show the critical role of renewable energy and environment-related technologies in fostering sustainable development and mitigating the environmental repercussions of trade within the BRICS context, providing valuable insights for policymakers in these economies.

Keywords: CO_2 Emissions, Trade, Everonment-Related Technology, Environment Policy Stringency, Renewable Energy, BRICS Panel Data, ARDL-PMG

JEL Classifications: C33, F64, O53, Q56, L52, O13

1. INTRODUCTION

International trade, which plays a key role in economic growth and development, is often associated with a significant increase in CO_2 emissions and pollution. This negative environmental impact of trade is particularly pronounced in the BRICS[1] countries. Trade can increase CO_2 emissions in BRICS countries due to their fast economic expansion, driven by rapid industrialization, which heavily relies on fossil fuels. This reliance to non-renewable sources leads to higher emissions, particularly through an export-oriented growth strategy (Bhat, 2018; Bilan et al., 2019; Idroes et al., 2024). These countries hold an increasingly important position in global trade and are major exporters of energy-intensive goods, such as manufactured products from China and India and raw materials from Brazil and Russia, which require significant amounts of energy, often derived from coal, oil, and gas. The export of carbon-intensive products, like coal from South Africa and steel from China, further amplifies their global emissions footprint. Additionally, the transportation of goods across global supply chains contributes to emissions (Liu, 2021), while deforestation for agricultural exports in Brazil releases stored CO_2. As BRICS countries play an increasingly central role in global trade, their expanding industrial and export activities substantially elevate CO_2 emissions (Khattak et al., 2020; Fu et al., 2021). Furthermore, the

1 Brazil, Russia, India, China, and South Africa

need for improved transportation logistics and infrastructure, such as ports and transportation networks, to support trade amplifies these emissions. BRICS countries represent a significant share of global trade, and their influence on pollution is growing. This position offers economic opportunities but also comes with responsibilities for their environmental impact. As these countries integrate into the global market, it is important to assess how their trade affects CO_2 emissions. We must also identify solutions to mitigate these effects. Addressing this challenge is crucial in the fight against climate change. Energy Information Administration (EIA) data (2023) reveals a significant surge in CO2 emissions from BRIC countries. Figures 1 and 2 illustrate this trend, showing their share of global emissions climbing from 28% in 2000 to 47.3% in 2020.

The literature highlights three variables as potential levers to mitigate the positive effects of trade on CO_2 emissions: Renewable energy (Arshad et al., 2024; Ahmad and Majeed, 2019; Kwilinski et al., 2024; etc.), environment-related technologies (Mongo et al., 2021; Hussain et al., 2022; Liu et al., 2022; etc.) and environmental policy stringency (Rehman et al., 2024; Frohm et al., 2023; Kartal et al., 2024; etc.). Studies on regions (panel data) and countries (time series) have shown that these three variables can reduce CO_2 emissions. Renewable energy reduces emissions by substituting fossil fuels in electricity generation and certain industrial processes. Environment-related technologies, such as carbon capture and storage or cleaner production processes, enhance energy efficiency and contribute to limiting emissions. Environment stringency policies can impose higher standards and encourage the adoption of more sustainable practices, thereby modifying the behavior of businesses and consumers to reduce CO_2 emissions.

Given these elements, our main objective in this study is to analyze the interactions between trade and these three variables on CO_2 emissions in the BRICS countries. Specifically, we aim to determine whether these variables can help mitigate the negative environmental effects of trade. For this objective, we use panel data related to BRICS countries for the period 2000-2020 and the ARDL-PMG approach. The choice of this approach is justified in section 3.

The relevance of this study lies in its dual examination: it not only analyzes the direct impact of various variables on CO_2 emissions such as international trade, renewable energy, environment-related technologies, environmental policies, and other independent variables, but also delves into the interaction effects between trade and the three aforementioned variables. This approach aims to identify how these interactions can serve as effective solutions for mitigating the positive impact of international trade on CO_2 emissions in BRICS countries.

If our results confirm our hypothesis, they could provide valuable insights for developing economic policies and strategies that balance economic growth with environmental protection in these countries. By reducing the positive effect of trade on CO_2 emissions, these strategies could support both a sustainable future and continued economic development.

Figure 1: Trends in CO_2 emissions (million tonnes) from 2000 to 2020

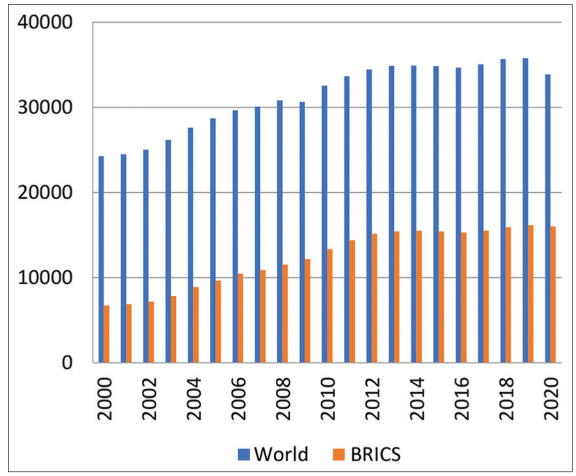
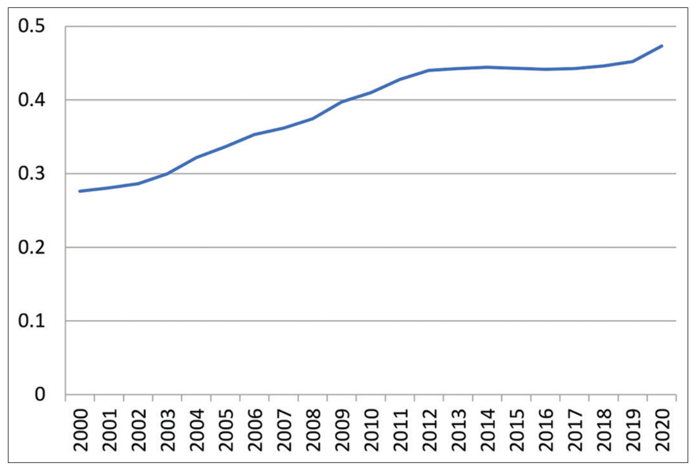


Figure 2: CO_2 emissions: Share BRIC/word



Authors, using EIA (2023) database

The remainder of the paper is structured as follows: Section 2 provides a comprehensive literature review, synthesizing findings from studies that explore the effects of trade, environment-related technologies, environment policy stringency, and renewable energy on CO_2 emissions across diverse regions and countries. Section 3 describes the data, outlines the empirical model, and explains the methodology employed in the analysis. Section 4 presents and discusses the results, drawing comparisons with existing literature to highlight key insights. Finally, Section 5 summarizes the main findings and offers actionable policy recommendations to address the identified challenges.

2. LITERATURE REVIEW

2.1. The Effect of Trade on CO_2 Emissions

Several studies are interested in the impact of trade on CO_2 emissions. Different methods, such as OLS, FMOLS, DOLS, ARDL, and nonlinear approaches like NARDL, are employed. The literature shows a controversy regarding the nature of the effect of trade on CO_2 emissions. Several studies, including those of Hdom and Fuinhas (2020) for Brazil and Liu (2021) for China, Kalaycı and Hayaloğlu (2019) for NAFTA countries, Yahyaoui and Ghandri (2024) and Farhani et al. (2013) for MENA countries and Dlamini et al. (2024) for Sub-Saharan Africa countries, find a significant and positive effect of trade on CO_2 emissions, driven by factors such as increased production (Arshad et al., 2024) transportation activities and energy consumption, associated with trade.

Other research suggests that trade can also contribute to emission reductions (Ahmed and Le, 2021; Suleman et al., 2024; Leitão, 2021; Dogan et al., 2017) For instance, Balogh (2022) demonstrates that agricultural exports can mitigate greenhouse gas emissions in non-EU countries. The environmental impact of trade is further influenced by various factors. Renewable energy emerges as a crucial mitigating factor, as evidenced by Liu, (2021) and Ahmed and Le (2021). Moreover, the characteristics of trade itself significantly influence its environmental impact. Studies on trade diversification, such as Wang et al. (2024) for OECD and G20 countries, and South-South trade, as explored by Meng et al. (2018), reveal uneven distributional impacts and show the importance of considering global and regional trade dynamics. Furthermore, the literature emphasizes the heterogeneity of trade's impact across countries and regions. While trade openness can reduce emissions in certain contexts, such as in high-income countries (Wang and Zhang (2021) and in specific sectors like agriculture (Balogh, 2022), its impact varies significantly. Factors such as income level, technological advancement, and the structure of trade all play crucial roles in determining the net environmental effect of trade.

Overall, the literature suggests that the relationship between trade and CO_2 emissions is complex: while trade can contribute to emission reductions under certain conditions, such as when combined with renewable energy, economic diversification, and higher income levels, its environmental impact is often influenced by a multitude of factors.

2.2. The Effect of Environmental-Related Technologies on CO_2 Emissions

Several studies focus on how environment-related technologies (ERT) and innovations affect CO_2 emissions in different country groups. These studies have found important results that show how ERT can help lower emissions. However, they also point out challenges that still need to be addressed. Dehdar et al. (2022) investigated the key drivers of CO_2 emissions across 36 OECD countries. Their study notably highlights the crucial role of environmental patents and environmental taxes in mitigating emissions. In their analysis of G7 countries, Voumik et al. (2023) reveal that fossil fuel-based electricity generation, particularly from coal and gas, is positively correlated with CO_2 emissions. Conversely, they highlight that renewable sources and nuclear energy contribute to lower emissions, emphasizing the importance of adopting low-emission technologies like solar and hydroelectric power for reducing greenhouse gas emissions. In European countries. Mongo et al. (2021) analyzed data from 15 European countries. They found that environmental innovations can lead to long-term emission reductions but may also induce a short-term rebound effect, temporarily increasing emissions. In their study of the EU transportation sector involving multiple countries, Kwilinski et al. (2024) find a significant negative correlation between the adoption of environmental technologies and CO_2 emissions, indicating that a 1% increase in these technologies results in a 0.35% reduction in emissions, underscoring the necessity of investing in green innovations. Similarly, Umar Farooq et al. (2023) examine several European economies and demonstrate that both renewable energy and technological innovations significantly lower CO_2 emissions, with a 1% increase in innovations correlating with a 0.146% decrease in emissions, while also linking economic growth and non-renewable energy use to higher emissions. Conversely, Alataş (2022) analyzed the transport sector in 15 EU countries and found that contrary to expectations, environmental-related technologies had a small and statistically insignificant positive effect on CO_2 emissions, suggesting that these technologies alone may not be sufficient for significant emissions reductions. In BRICS, Hussain and Dogan (2021) find that ERT significantly lowers ecological footprints, indicating that improving ERT can effectively mitigate environmental degradation. They emphasize the need for enhanced institutional quality and increased investments in these technologies to support sustainable development. In the context of BRIICS countries, Cheng et al. (2019) demonstrate that renewable energy supply has a significant negative impact on CO_2 emissions per capita, particularly at higher emission quantiles. However, they also note that the development of environmental patents can be associated with increased emissions at upper quantiles, suggesting that while innovation drives progress, it may not always lead to immediate reductions in carbon emissions due to implementation challenges.

Other studies examining selected developed and developing countries demonstrate that economic context and technological capacity significantly influence the relationship between environmental-related technologies (ERT) and CO_2 emissions. Hussain et al. (2022) investigate seven emerging economies (China, India, Brazil, Mexico, Russia, Indonesia, and Turkey) and find that ERT notably reduces consumption-based carbon emissions, particularly when bolstered by investments in renewable energy and during periods of GDP growth. In Nordic countries, Ahmed et al. (2022) analyze the relationship between cyclical innovation in green technologies and CO_2 emissions, revealing that while innovations can mitigate emissions during economic growth, negative shocks in these technologies can lead to increased emissions during downturns. Chen and Lee (2020) examined the impact of technological innovation on CO_2 emissions across 96 countries, revealing a significant disparity in its effects. While high-income, technologically advanced economies tend to benefit from reduced emissions due to technological advancements, the study suggests that these benefits may not be evenly distributed. Technological innovation may even lead to increased emissions in other countries. They emphasize that the effectiveness of innovation varies significantly based on income level and technological capability.

Research on the impact of environment-related technologies (ERT) and innovations on CO_2 emissions at the country level is limited due to the scarcity of available data for this variable, highlighting the varying impacts. Among these studies, the following results can be cited: In China, Chang et al. (2023) analyze data from 30 provinces between 2003 and 2019, finding that local environmental regulations significantly enhance the positive effects of green technology innovation (GTI) on CO_2 emissions reduction, with investment-based regulations being the most effective. Liu et al. (2022) further examine this relationship using a panel dataset from 30 Chinese provinces from 2008 to 2019, revealing a coefficient of −0.083 for technological innovation, indicating that a 1% increase in innovation leads to a 0.083% reduction in carbon emissions, along with significant spatial spillover effects. Similarly, in China, Zhang et al. (2021) provide a qualitative review of various carbon emission reduction technologies, emphasizing the need for increased investment to overcome challenges related to technology maturity. In the United States, Hongqiao et al. (2022) find a significant long-run relationship where a 1% increase in environmental innovation corresponds to a 0.6444% reduction in CO_2 emissions, supporting the Environmental Kuznets Curve hypothesis. Xin et al. (2021) explore how innovations in environmental-related technologies (IERT) impact CO_2 emissions in the USA, concluding that while IERT reduces emissions during economic growth, it can lead to higher emissions during recessions if not adequately supported. In Saudi Arabia, Islam et al. (2024) assess the impact of environmental technology (ET), finding its influence on reducing CO_2 emissions limited due to low adoption rates relative to the country's technological capacity.

2.3. The Effect of Environmental Policy Stringency on CO_2 Emissions

The relationship between environmental policy stringency (EPS) and CO_2 emissions has been extensively explored in the literature. Several studies have investigated the effects of EPS on CO_2 emissions and air quality across various countries and regions over different periods. Utilizing a range of econometric methods, such as ARDL-PMG, NARDL, MMQR, and FMOLS, researchers have analyzed how stricter policy environment regulations influence emission levels across multiple sectors and national contexts. Most studies focus on panel data from regions like OECD countries, BRICS, and EU member states or selected countries. While findings may vary across contexts, a significant body of research suggests that stricter environmental policies generally lead to lower CO_2 emissions. This large literature offers valuable insights for policymakers aiming to implement successful environmental initiatives.

Studies consistently demonstrate a negative correlation between environmental policy stringency (EPS) and CO_2 emissions within OECD countries. Ahmed (2020), analyzing data from 20 OECD countries, found that stricter policies foster green technology and sustainable development. Rehman et al. (2024) further support these findings, showing that stricter environmental policies encourage renewable energy adoption in OECD countries, reducing reliance on fossil fuels. Mihai et al. (2023) find that market-based instruments, when combined with stringent policies, are particularly effective in reducing greenhouse gas emissions and promoting renewable energy consumption. Frohm et al. (2023) further emphasize the significance of stringent policies, demonstrating that they lead to substantial emissions reductions, particularly in high fossil fuel-dependent sectors within 30 OECD countries. In the European region, studies also show a negative impact of environmental policy stringency on CO_2 emissions. Godawska (2021) finds that stricter environmental policies lead to lower levels of air pollution across 18 EU countries, concluding that increasing policy stringency can significantly improve air quality and public health. Similarly, Wolde-Rufael and Mulat-Weldemeskel (2021) demonstrate that both environmental taxes and stringent policies effectively reduce CO_2 emissions in 20 European countries, emphasizing the need for policymakers to raise environmental taxes to meet climate change objectives. Kartal et al. (2024) further explore the varying effects of environmental policy stringency on sectoral CO_2 emissions in five European countries (Germany, Spain, France, the United Kingdom, and Italy) revealing that while stringent policies can reduce emissions, their effectiveness varies by sector and country. This highlights the necessity of specific approaches that consider the diverse structures of environmental measures and focus on particular sectors to optimize emissions reductions.

The negative effect of policy stringency on CO_2 emissions is also confirmed by certain studies relative to BRICS and G7 countries. Indeed, Wolde-Rufael et al (2023, 2021, 2020) identify an inverted U-shaped relationship, indicating that stricter policies initially have limited impact but become effective after reaching a certain threshold, while emphasizing the need for enhanced regulations to improve air quality. Sezgin et al. (2021) find a two-way relationship between environmental policies and CO_2 emissions in G7 countries, noting that stronger policies and better human development contribute to lowering emissions. Güler and Doğan (2023) confirm that stricter environmental policies lead to lower carbon emissions in G7 countries, while innovation tends to increase emissions, highlighting the necessity of strong regulations. Li et al. (2023) and Udeagha and Ngepah (2023) report that stricter environmental policies effectively reduce CO_2 emissions in BRICS countries, noting the positive impact of green innovation and renewable energy R&D. However, Mahalik et al. (2024) caution that strict environmental policies alone may not suffice for emissions reduction in BRICS, as trade and foreign direct investment can exacerbate emissions.

There are also several studies that have examined the effect of environmental policy stringency on CO_2 emissions using panel data from selected countries (developed and developing). Probst and Sauter (2015) find that adopting the strict policies of the most regulated country can reduce CO_2 emissions by 15%, indicating that stricter policies enhance sectoral efficiency, with lower costs for developing nations. Liu et al. (2023) reveal that positive shocks in environmental policy stringency significantly reduce emissions in the most polluted Asia-Pacific countries, while negative shocks increase emissions, highlighting the importance of human capital and renewable energy for environmental quality. In contrast, Alexandersson (2020) argues that stricter policies do not substantially lower emissions, noting that fossil fuel consumption and gasoline prices exert a stronger influence, suggesting that raising gasoline prices could be effective. Chi (2025) shows a clear negative correlation between stricter environmental policies and transportation CO_2 emissions, emphasizing that the combined effect of electric vehicles and stringent policies is more impactful than either factor alone. Tiwari et al. (2024) assert that stricter policies significantly reduce emissions in high-GDP countries, reinforcing the necessity for strong regulations. De Angelis et al. (2019) indicate that stricter policies lead to lower emissions and demonstrate an inverted U-shaped relationship between GDP per capita and emissions. Assamoi and Wang (2023) confirm that stricter environmental policies decrease emissions in both China and the USA, despite the differing effects of economic policy uncertainty. Yirong (2022) finds that stricter policies result in lower emissions over time in major polluting countries, even amidst relaxed policies.

For individual countries, there are not many studies that examine the effect of environmental policy stringency on CO_2 emissions, but we can cite those related to China. Chen, M. et al (2022) find that positive changes in environmental policy stringency significantly reduce CO_2 and greenhouse gas emissions, while negative changes result in increased emissions, emphasizing that strong environmental policies are crucial for improving air quality in China. Similarly, Ahmed and Ahmed (2018) reveal that while strict environmental policies can help reduce CO_2 emissions, they also negatively impact GDP growth.

2.4. The Effect of Renewable Energy on CO_2 Emissions

Several studies investigate the effect of renewable energy on CO_2 emissions in different regions and countries. Most of these studies show that renewable energy reduces emissions, but results can vary based on location and other factors. In developed countries, literature shows a significant role of renewable energy in mitigating emissions. For example, Cheng et al. (2019) studied 35 OECD countries and found an inverted U-shaped relationship, suggesting that the effectiveness of renewable energy varies with different levels of per capita CO_2 emissions, ultimately rejecting the Environmental Kuznets Curve (EKC) hypothesis. In contrast, Rahman et al. (2022) support the EKC hypothesis in 22 developed countries, demonstrating that renewable energy significantly decreases CO_2 emissions as economic development progresses. Voumik et al. (2023) examined G7 countries and uncovered a positive correlation between fossil fuel-based electricity generation and CO_2 emissions, emphasizing the importance of renewable and nuclear energy sources in emissions reduction. In the European region, studies by Grodzicki and Jankiewicz (2022) and Petruška et al. (2022) also reveal a negative relationship between renewable energy and CO_2 emissions. They show that a 1% increase in renewable energy results in a 0.5% decrease in CO_2 emissions per person, while Busu (2019) finds that a 1% rise in renewable energy consumption reduces emissions by about 108,000 tons. Huang et al. (2021) further confirm this negative effect of renewable energy on CO2 emissions in major renewable energy-consuming countries. According to their study CO2 emissions decrease by 0.5 % if renewable energy increase by 1%. Wang et al. (2022) indicate that established technologies such as geothermal and hydropower are more effective at reducing emissions than newer options like solar and wind. In the transportation sector, Kwilinski et al. (2024) identify a negative relationship between environmental technologies, including renewable energy, and CO_2 emissions. Leitão (2014; 2021) also explores this topic, showing that economic growth may initially increase emissions, and integrating renewable energy is essential for achieving reductions. His 2014 study on Portugal shows a positive correlation between renewable energy consumption and economic growth, significantly lowering CO_2 emissions, while the 2021 study covering five European countries finds that renewable energy mitigates emissions increases linked to corruption and economic development. In the USA, Silva et al (2012), Sharif et al. (2021) and Hongqiao et al. (2022) demonstrate that renewable energy plays a crucial role in reducing CO_2 emissions. Sharif et al. analyze various renewable sources and suggest that while renewable energy consumption typically lowers emissions, its effectiveness varies based on the specific source and context. Similarly, Chen, C. et al. (2022) demonstrate through their analysis of 97 countries that renewable energy's impact on CO_2 emissions is not automatic. Their findings reveal that renewable energy consumption only significantly reduces CO_2 emissions after surpassing a specific adoption threshold In Asia, findings are mixed. Ahmad and Majeed (2019) reveal that increased renewable energy consumption in South Asian countries correlates negatively with CO_2 emissions, whereas reliance on fossil fuels elevates emissions. Similarly, Idroes et al. (2024) find that in Indonesia, coal and gas significantly increase CO_2 emissions, while renewable energy reduces both emissions and ecological footprints. However, Hasnisah et al. (2019) validate the EKC hypothesis in 13 developing Asian countries but find that the effect of renewable energy on emissions is statistically insignificant due to its low share in the energy mix. Liu et al. (2023) emphasize the need for stringent environmental policies alongside renewable energy to significantly decrease CO_2 emissions in the Asia-Pacific's most polluted countries. Liu (2021) and Zhang et al. (2021) also highlight the essential role of renewable energy in reducing emissions in China, noting that while trade and non-renewable energy consumption increase emissions, renewable energy effectively mitigates them despite challenges like geographic constraints and technological maturity. In the MENA region, Yahyaoui and Ghandri (2024) find that renewable energy significantly reduces emissions, while economic growth and trade openness tend to increase them, presenting an inverted U-shaped relationship that challenges traditional expectations. In contrast, Kahia et al. (2019) identify a bidirectional relationship where renewable energy lowers emissions, but economic growth raises them. Regarding BRICS countries, Cheng et al. (2019) examine the heterogeneous effects of renewable energy supply and environmental patents on per capita CO_2 emissions. Their findings indicate that while renewable energy significantly reduces emissions, environmental patents may inadvertently contribute to increased emissions due to implementation complexities. Khattak et al. (2020) further investigate the relationship between innovation and renewable energy consumption, concluding that renewable energy effectively mitigates emissions in most BRICS countries, although innovation can lead to emissions in China, India, Russia, and South Africa. Fu et al. (2021) identify a unidirectional causality from renewable energy to CO_2 emissions, suggesting that increased renewable energy consumption leads to lower emissions.

Mamkhezri et al. (2024) investigate the spillover effects of renewable energy use and R&D investments on CO2 emissions using panel data from 54 countries. Their findings reveal that R&D

expenditures reduce emissions through two key channels: a direct intensity effect driven by technological innovation and indirect spillover effects that enhance renewable energy deployment and steer economic growth toward greener pathways. While renewable energy expansion generally mitigates emissions, the study highlights that its effectiveness is contingent upon a country's existing energy composition and level of R&D advancement.

In conclusion of this literature review, while numerous studies have investigated the individual impacts of trade, renewable energy, environment-related technology and environment policy stringency on CO_2 emissions, research specifically examining the interaction effects between trade and these three factors is limited. This study aims to fill this gap by analyzing whether these factors can effectively mitigate the positive impact of trade on CO_2 emissions. Moreover, the selection of BRICS countries as our sample is crucial, given their significant contribution to global pollution and their rapid economic growth, making them a critical case for understanding the interplay between trade and environmental factors.

3. DATA AND METHODOLOGY

3.1. Data

This paper has two main objectives. First, we examine the long-term and short-term effect of renewable energy, environment-related technology, policy stringency, trade, and other variables including industry value added, population, non-renewable energy, and geopolitical risk on CO_2 emissions in BRICS countries between 2000 and 2020. The choice of this period is explained by the availability of data for the variables environment-related technology and policy stringency. Second, we explore the long-term and short-term effects of interactions between trade and environment-related technology, trade and policy stringency, and trade and renewable energy on CO_2 emissions. We use these three interaction effects to understand how strategies focused on environment-related technology, policy stringency, and renewable energy can mitigate the positive impact of trade on CO_2 emissions. To achieve this, we adopted the following empirical specifications

$$CO2_{it} = f(AVINDit, POPit, GPRit, TRADEit, REit, NREit, ERTit, EPSit) \quad (1)$$

$$CO2_{it} = f(AVINDit, POPit, GPR, TRADEit, TRADE*REit, TRADE*ERTit, TRDE*EPSit) \quad (2)$$

CO_2, AVIND, POP, GPR, TRADE, RE, NRE, ERT, and EPS represent, respectively, carbon dioxide emissions, industry (including construction) value added, population, geopolitical risk index, trade, renewable energy, non-renewable energy, environment-related technology, and environment policy stringency. (i) denotes country i and (t) denotes year t since we use annual panel data. CO_2 *emissions* are a key indicator of environmental pollution. The main sources of CO_2 emissions are the combustion of coal, natural gas, oil and other fuels that hurt the environment. Industry value added is an indicator of economic growth, its values are expressed in trillions of dollars, adjusted for purchasing power parity (PPP) and reported in 2015 dollars.

The Environment-related technology includes tools and systems used to protect the environment and promote the efficient use of resources. The main goal of these technologies is to improve environmental quality. We measure this variable by the The Environment-related technology index (ERT) calculated by the OECD. Similarly, environmental policy stringency measures how strict a country's environmental policies are in discouraging pollution and harmful activities. TIt is measured by the OECD environmental policy stringency index (EPS).

The geopolitical risk index is a measure that quantifies the level of geopolitical risks faced by countries. It captures factors such as political instability, conflicts, and tensions that could impact economic and social stability (international relations, trade, investments, or security, etc). We use Geopolitical Risk Index calculated by Dario Caldara and Matteo Iacoviello at the Federal Reserve Board. Table 1 below summarises the symbols, measurement units, and sources for the various variables.

3.2. Methodology

3.2.1. Descriptive statistics

Descriptive statistics provide a comprehensive overview of the data, revealing key insights into the variability and distribution of critical variables across BRICS countries over time. As shown in Table 2, the average CO_2 emissions among BRICS nations is 2451.844 million metric tons (MMt), with a substantial standard deviation of 3142.727 MMt. This indicates a wide range of emissions, spanning from a minimum of 322.7108 MMt to a maximum of 10,841.55 MMt, highlighting significant disparities in carbon footprints across these countries. Similarly, Industry Value Added (AVIND) exhibits considerable variation, with the average exceeding the median and a standard deviation of 1.36×10^{12}. The gap between the maximum (5.77×10^{12}) and minimum (6.27×10^{10}) values is striking, largely driven by China's dominant industrial output compared to the other BRICS nations, as illustrated in Figure 3. Population distribution further underscores the heterogeneity within BRICS. China and India, the two most populous countries, contrast sharply with Brazil, Russia, and South Africa, the latter having the smallest population among the five. This demographic divergence directly influences energy consumption patterns and, by extension, CO_2 emissions, as larger populations typically drive higher energy demands and increased emissions.

Additionally, environment-related technology and Environmental Policy Stringency display notable variability. The average values for these variables (87.27943 and 109.5238, respectively) exceed their medians (61.27613 and 86.11111), reflecting significant differences in environmental innovation and regulatory rigor across BRICS countries. Similarly, renewable and non-renewable energy consumption exhibit pronounced disparities.

The mean values for renewable (3.169178 QBtu) and non-renewable (30.68428 QBtu) energy consumption are higher than their medians (1.714666 and 20.45394 QBtu, respectively), with maximum values far exceeding the minimums. his indicate an uneven distribution of energy use and environmental policies, underscoring the diverse economic and environmental landscapes within the BRICS countries

Table 1: Variables definitions

Variables	Symbol	Unit of measurement	Sources
Carbon dioxide emissions	CO_2	MM tonnes	EIA (2023)
Renewable emergy	RE	QBTU	
Non- renewable energy	NRE		
Industry value added	AVIND	constant 2015 USD	WDI (2023)
Population	POP	Total number of inhabitants	
Trade		Index	
Environmnet-related technology	ERT	Index	OECD (2024)
Environmental policy stringency	EPS	index	EIA (2024)
Geopolitical risk	GPR	Index	Policyuncertainty.com, (2024)

Table 2: Descriptive statistics

Statistic \ Variables	CO_2	ERT	POP	EPS	AVIND	GPR	RE	NRE	TRADE
Mean	2451.844	87.27943	5.94E+08	109.5238	8.80E+11	354.1046	3.169178	30.68428	44.25049
Median	1535.638	61.27613	1.96E+08	86.11111	3.62E+11	241.8051	1.714666	20.45394	46.51812
Maxim	10841.55	649.8263	1.41E+09	313.8889	5.77E+12	1368.852	19.00387	133.2680	68.09391
Minim	322.7108	4.181454	46813266	16.66667	6.27E+10	30.68151	0.006379	4.426901	22.10598
Standard deviation	3142.727	98.79327	5.75E+08	78.60033	1.36E+12	338.5006	3.856692	36.48522	11.98508
J. Bera	69.12028	1022.724	16.59209	20.64771	172.7824	21.94006	224.7346	66.95827	5.726423
Prob	0.000000	0.000000	0.000250	0.000033	0.000000	0.000017	0.000000	0.000000	0.057085
N	105	105	105	105	105	105	105	105	105

CO_2, **ERT**, POP, **EPS**, AVIND, GPR, RE, NRE, and TRADE correspond to CO_2 emissions, Environment-related technology, population, Environmental Policy Stringency, Industry Value Added, geopolitical risk, renewable energy, non-renewable energy, and trade, respectively

Table 3: Cross-sectional dependence (CD) test

Pesaran CD Test	Statistic	Probability
Specification 1	−1.551973	0.1207
Specification 2	−0.870897	0.3838
Specification 3	−0.441526	0.6588
Specification 4	−1.171283	0.2415
Specification 5	−1.382850	0.1667

3.2.2. Cross-sectional dependence (C-SD) test

In this section, we examine the presence of cross-sectional dependence (CD) in the residuals, which is essential for determining the appropriate choice between first and second-generation panel unit root tests (PURT). Numerous tests are referenced in the empirical literature, including the Breusch-Pagan Chi-square, Pearson LM Normal, Pearson CD Normal, Friedman Chi-square, and Frees Q tests. The null hypothesis for these tests asserts that cross-sectional independence exists, signifying no significant correlations. The results of the cross-sectional dependence (C-SD) tests, using the Pearson CD test (Table 3), show that the null hypothesis cannot be rejected across all specifications. This confirms the absence of significant cross-sectional dependence in the residuals, justifying the use of first-generation PURT for this analysis.

3.2.3. Panel unit root tests (PURT)

In the following section, we test the stationarity of the used variables. We want to see if these variables are stable over time or if they show non-stationary trends. To get accurate results and avoid errors, we use unit root tests. We apply two common tests: the Augmented Dickey-Fuller (ADF, 1979) and Phillips-Perron (PP, 1988) tests.

The results, presented in Table 4, show that all variables are not stationary at their level. However, they become stationary after taking the first difference. This finding allows us to check for long-run cointegration among the variables. To explore this, we will apply the Pedroni test, which is a robust method for analyzing cointegration in panel data.

3.2.4. Pedroni cointegration test results

To assess the long-run cointegration between CO_2 emissions and the independent variables, we used the seven cointegration tests developed by Pedroni (2001) for each specification. These tests are categorized into two groups: Intra-dimension and inter-dimension. The results are summarized in Table 5. Within the intra-dimension category, which includes four tests (Panel v, Panel rho, Panel PP, and Panel ADF), the Panel v and Panel rho tests did not provide evidence of cointegration. In contrast, the Panel PP and Panel ADF tests strongly supported the presence of cointegration. Similarly, in the inter-dimension category, which consists of three tests (Panel rho, Panel PP, and Panel ADF), the Panel rho test failed to reject the null hypothesis of no cointegration. However, the Panel PP and Panel ADF tests confirmed the existence of cointegration.

In summary, four out of the seven tests indicated significant evidence of long-term cointegration among the variables. This finding allows us to confidently proceed with long-term estimation.

4. RESULTS AND DISCUSSION

4.1. Emptical Model and Results

We employ the ARDL-PMG approach for several key reasons. First, our previous Panel Unit Root Test results indicate that all variables are stationary at either level or first difference, which satisfies the model's requirements. Second, the ARDL-PMG model allows us to examine both short-term and long-term effects simultaneously. Third, it is particularly well-suited for small sample sizes, making it an ideal choice for our study, which focuses on only five countries. Finally, the ARDL-PMG approach effectively addresses common econometric issues such as endogeneity,

Figure 3: Evolution of Key Variables in BRICS Countries (2000-2020)

Table 4: Panel unit root tests (PURT)

	At level	$lnCO_2$	lnAVIND	LnRE	lnNRE	lPOP	lnTRADE	lnGPR	lnEPS	lnERT
ADF	t-Statistic	0.91458	2.01976	1.54367	0.91864	5.45708	7.76672	7.20684	1.11460	2.23306
	Probability	0.9999	0.9962	0.9988	0.9999	0.08586	0.6516	0.7058	0.9997	0.9942
	First dif	d ($lnCO_2$)	d (lnAVIND)	d (lnRE)	d (lnNRE)	d (lnPOP)	d (lnTRADE)	d (lnGPR)	d (lnEPS)	d (lnERT)
	t-Statistic	32.4560	23.1870	51.4061	28.6137	20.8341	53.7204	75.5876	49.8265	52.0601
	Probability	0.0003	0.0101	0.0000	0.0014	0.0223	0.0000	0.0000	0.0000	0.0000
PP	At level	$lnCO_2$	lnAVIND	lnRE	lnNRE	lnPOP	lnTRADE	lnGPR	lnEPS	lnERT
	t-Statistic	0.47357	0.55016	0.76564	0.26764	2.21995	9.61092	8.15119	0.80200	1.84008
	Probability	1.0000	1.0000	1.0000	1.0000	0.9944	0.4753	0.6141	0.9999	0.9974
	First dif	d ($lnCO_2$)	d (lnAVIND)	d (lnRE)	d (lnNRE)	d (lnPOP)	d (lnTRADE)	d (lnGPR)	d (lnEPS)	d (lnERT)
	t-Statistic	66.5452	32.3894	73.8039	60.0826	61.0048	90.6588	112.414	69.6873	72.8743
	Probability	0.0000	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

heteroscedasticity, autocorrelation, and multicollinearity, ensuring the robustness and reliability of our results.

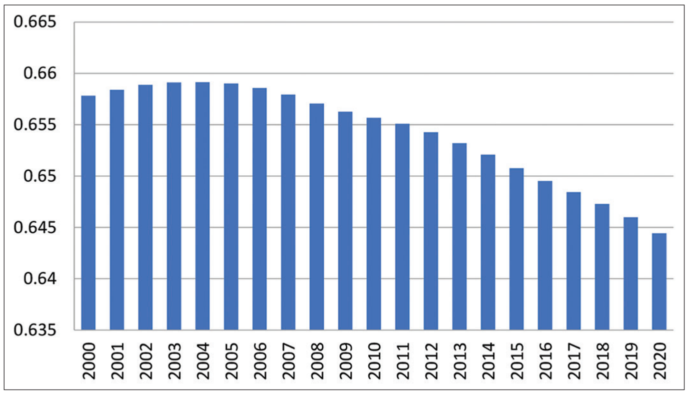
We used the following specification of the panel ARDL (p, q) model proposed by Pesaran et al. (1999).

Table 5: Pedroni cointegration test results

Cointegration test / Specification	Panel (within-dimension)				Group (between-dimension)		
	Panel v-statistic	Panel rho-statistic	Panel PP-statistic	Panel ADF-statistic	Group rho-statistic	Group PP-statistic	Group ADF-statistic
Specification 1	−0.50316	2.116998	−1.68621**	−1.811362**	2.878191	−1.916006**	−1.44762**
Specification 2	−0.95025	1.585597	−1.944895*	−1.166233**	2.591495	−3.00823***	−1.375701*
Specification 3	−0.18392	1.824467	−1.7612**	−1.42996**	2.525054	−2.45899***	−1.160725*
Specification 4	−0.22682	0.712455	−5.2644***	−2.90849***	1.428944	−7.45971***	− 3.6345***
Specification 5	−0.31203	1.853818	−3.9856***	−2.76752***	2.742720	−5.30016***	3.41591***

*, ** and ***indicates statistical significance at the 10%, 5% and 1% level respectively

Figure 4: Share of BRICS population in global population (%)



Source: Authors, using WDI database

$$lnCO2_{it} = +\alpha_i + \sum_{j=1}^{p-1}\beta_{1ij}\, lnCO2_{it-j} + \sum_{j=0}^{q-1}\beta_{2ij}\, AVIND_{it-j} + \sum_{j=0}^{q-1}\beta_{3ij}\, GOPRK_{it-j} + \sum_{j=0}^{q-1}\beta_{4ij}\, lnRE_{it-j} + \sum_{j=0}^{q-1}\beta_{5ij}\, TRADE_{it-j} + \sum_{j=0}^{q-1}\beta_{6ij}\, lnNRE_{it-j} + \sum_{j=0}^{q-1}\beta_{7ij}\, lnERT_{it-j} + \sum_{j=0}^{q-1}\beta_{8ij}\, lnEPS_{it-j} + \sum_{j=0}^{q-1}\beta_{9ij}\, lnPOP_{it-j} + \varepsilon_{it} + \sum_{j=0}^{q-1}\beta_{10ij}\, \ln(TRADE*X)_{it-j} \quad (3)$$

Where ($TRADE*X$) represents the interaction term between trade and the variable X. the variable X can take the form of renewable energy (RE), (RE), Environment policy stringency (EPS) or Environment related-technology (ERT).

We adopt five specifications based on this general form. In the first specification, we examine the effects of various variables on CO_2 emissions without accounting for interaction effects. Subsequently, in specifications 2, 3, and 4, we separately estimate the interaction effects of trade with renewable energy, environment-related technology, and environmental policy stringency. Finally, in the fifth specification, we combine the interaction effects of trade with all three previously mentioned variables. We transformed variables into logarithmic form to interpret the estimated coefficients as elasticities. This approach facilitates a clearer understanding of how CO_2 emissions respond to changes in the explanatory variables.

According to the work of Pesaran et al. (1996; 2001), the equation (3) can be expressed in the following alternative form:

$$\Delta lnCO2_{it} = +\alpha_i + \partial_{1i} lnCO2_{it-1} + \partial_{2i} lnAVIND_{it-1} + \partial_{3i} lnGPRK_{it-1} + \partial_{4i} lnRE_{it-1} + \partial_{5i} lnTRADE_{it-1} + \partial_{6i} lnNRE_{it-1} + \partial_{7i} lnERT_{it-1} + \partial_{8i} lnEPS_{it-1} + \partial_{9i} lnPOP_{it-1} + \partial_{10i} ln(TRADE*X)_{it-1} + \sum_{j=1}^{p-1}\delta_{1ij}\, \Delta lnCO2_{it-j} + \sum_{j=0}^{q-1}\delta_{2ij}\, \Delta lnAVIND_{it-j} + \sum_{j=0}^{q-1}\delta_{3ij}\, \Delta lnGPRK_{it-j} + \sum_{j=0}^{q-1}\delta_{4ij}\, \Delta lnRE_{it-j} + \sum_{j=0}^{q-1}\delta_{5ij}\, \Delta lnTRADE_{it-j} + \sum_{j=0}^{q-1}\delta_{6ij}\, \Delta lnNRE_{it-j} + \sum_{j=0}^{q-1}\delta_{7ij}\, \Delta lnERT_{it-j} + \sum_{j=0}^{q-1}\delta_{8ij}\, \Delta lnEPS_{it-j} + \sum_{j=0}^{q-1}\delta_{9ij}\, \Delta lnPOP_{it-j} + \sum_{j=0}^{q-1}\delta_{10ij}\, \Delta lnTRADE*X_{it-j} + v_{it} \quad (4)$$

This equation differentiates between long-run and short-run effects through levels and first differences. The levels indicate long-run effects, while the first differences reflect short-run effects. The coefficients ∂ni and δni ($n = 1....10$) represent the long-term and the short-term effects, respectively. These parameters quantify how CO_2 CO_2 emissions respond to a one-unit change in each independent variable, holding all other variables constant. The term. v_{it} is the error term, and Δ means the first difference operator.

4.2. Discussion

The optimal lag length for the panel ARDL model is determined to be ARDL(1, 1, 1, 1, 1, 1,1,1,1), based on the Schwarz Information Criterion (SIC). Estimations show important results for understanding what affects CO_2 emissions, especially in the long term. First, the results indicate that coiefficient of the long-run adjustment term (ECT_{-1}) is negative and significant in all specifications. This means that there is a quick return to long-run balance when changes occur. In the short term, we see that only the non-renewable energy variable has a positive and significant effect on CO_2 emissions in all five specifications. Thisshows that non-renewable energy still causes pollution in BRICS countries. The other variables do not show significant effects, so we cannot make strong conclusions about them. For this reason, we will focus only on the long-term results in the next discussions.

The horizontal analysis of the results presented in Table 6 allows us to interpret the direct effects of the various independent variables on CO_2 emissions. Findings show that, across all five specifications, industrial growth, population growth, trade, and non-renewable energy have positive and significant effects on CO_2 emissions in

Table 6: ARDL-PMG estimates

Dependent variable: L CO_2					
Long run					
Independent variables	**Specification (1)**	**Specification (2)**	**Specification (3)**	**Specification (4)**	**Specification (5)**
LAVIND	0.039095**	0.033102*	0.033102*	0.039707*	0.039707*
LPOP	0.190484***	0.207187***	0.207187***	0.189289***	0.189289***
LNRE	1.081160***	1.074048***	1.074048***	1.082258***	1.082258***
LGPR	−0.013082*	−0.012842*	−0.012842	−0.013275*	−0.013275*
LTRADE	0.038784**	0.122344***	0.078673***	0.038811*	0.174143***
LRE	−0.077898***		−0.094192***	−0.07670***	
LERT	−0.057735***	−0.05052***		−0.05862***	
LEPS	0.000640	0.000741	0.000823		
LRE*TRADE		−0.09419***			−0.07670***
LERT*TRADE			−0.050521***		−0.05862***
LEPS*TRADE				0.000106	0.000106
Short run					
Independent variables	**Specification (1)**	**Specification (2)**	**Specification (3)**	**Specification (4)**	**Specification (5)**
ECT_{-1}	−0.444151**	−0.441357**	−0.441357**	−0.443083**	−0.443083**
D (LAVIND)	0.013947	0.014961	0.014961	0.014626	0.014626
D (LPOP)	−2.289453	−2.822933	−2.822933	−2.257164	−2.257164
D (LNRE)	0.484858**	0.492958**	0.492958**	0.484177**	0.484177**
D (LGPR)	0.004946	0.005280	0.005280	0.004951	0.004951
D (LTRADE)	−0.018576	−0.037495	−0.021811	−0.018731	−0.035186
D (LRE)	0.013790		0.017609	0.013207	
D (LERT)	0.002885	0.001925		0.003248	
D (LEPS)	−0.000351	−0.00528	−0.010466		
D (LRE*TRADE)		0.017609			0.013207
D (LERT*TRADE)			0.001927		0.003248
D (LEPS*TRADE)				−0.000134	−0.000134

- *, ** and *** indicates statistical significance at the 10%, 5% and 1% level respectively
- ECT_{-1} is the error correction term derived from the long-run relationship, and these coefficients should be negative

BRICS countries. In contrast, renewable energy, environment-related technology, and geopolitical risk exert negative and significant effects on CO_2 emissions, except in specification 3, where the coefficient for geopolitical risk is negative but not statistically significant. The coefficients for the variable environment policy stringency (EPS) are positive but not statistically significant, which prevents us from drawing any definitive conclusions regarding its effect on CO_2 emissions in BRICS countries. This suggests that the existing environmental policies may not be sufficiently effective in influencing emission behaviors in a meaningful way. The growth of industrial activities is a major cause of CO_2 emissions, as economic growth in BRICS countries is linked to industrialization. This leads to higher energy use, from non-renewable sources like coal, oil, and gas. As these countries strive to enhance their economic growth, they invest more in industries, which increases their reliance on fossil fuels. This reliance, in turn, leads to more carbon emissions. The positive and significant impact of population on CO_2 emissions is largely due to high energy consumption. This is especially true in BRIC countries, which include the world's two most populous countries (India and China). As shown in Figure 4 below, during the period from 2000 to 2021, the share of the population of BRICS countries was nearly two-thirds of the global population.

Trade positively affects CO_2 emissions in BRICS countries due to the significant rise in energy consumption linked to increasing international trade and industrialization. According to the WTO report on international trade (2023), approximately 10% of global CO_2 emissions are attributed to this trade. The long-distance transport of goods, coupled with growing industrialization and demand for fossil energy, further drives up emissions. Large-scale production, often less sustainable, and increasing consumption exacerbate resource exploitation.

The vertical analysis of the results, specification by specification, enables us to interpret the effects of the interaction variables between trade and three key factors that may serve as strategies to reduce or mitigate the negative impact of trade on CO_2 emissions. these variables are: Renewable energy, environment-related technologies, and the stringency of environmental policies.

*Th*e specification2 examines the interaction effect between trade and renewable energy (TRADE*RE). This coefficient is negative and statistically significant (−0.09419). This result indicates that, in addition to its direct effect of reducing CO_2 emissions, renewable energy plays an indirect role in reducing or mitigating the positive impact of trade on emissions. This finding is important and supports recommendations to promote the use of renewable energy as a key strategy to reduce pollution associated with trade.

Similarly, Specification 3 examines the interaction effect between trade and environment-related technology (TRADE*ERT). This coefficient is also negative and statistically significant (−0.050521). This result indicates that environment-related technology also exerts an indirect effect, helping to mitigate the positive impact of trade on CO_2 emissions. It can be used as a tool or strategy to reduce the pollution effects linked to trade.

In Specification 4, we examined the interaction effect between trade and environmental policy stringency (TRADE*EPS). The estimated coefficient is positive but not statistically significant (0.000106), which does not provide evidence of an indirect effect of environmental policy stringency in mitigating the effect of trade on CO_2 emissions. This lack of an indirect effect is consistent with the absence of a clear direct effect of environmental policy stringency in reducing CO_2 emissions.

According to this result, environmental policy stringency has not yet played its role in BRIC countries as a decisive strategy for addressing emissions linked to trade.

In Specification 5, we simultaneously examined the combined effects of the three previous interaction terms on CO_2 emissions. The results are consistent with those found in Specifications 2, 3, and 4. Renewable energy and environment-related technology have indirect effects in mitigating the impact of trade on pollution. In contrast, environmental policy stringency does not appear to have any significant indirect effects. This result reinforces the importance of renewable energy and technological innovation as strategies for addressing trade-related emissions and highlights the limited influence of policy stringency.

5. CONCLUSION

in this This study we investigated the short-term and long-term effects of several key factors: Industrial value-added, trade, population, renewable and non-renewable energy, environmental technology, policy stringency, and geopolitical risk on CO_2 emissions in BRICS countries from 2000 to 2020. We conducted two types of tests. First, we estimated the direct effects of various independent variables on CO_2 emissions. Next, we examined how trade interacts with renewable energy, environment-related technology, and environmental policy stringency to assess their potential as effective strategies for reducing pollution associated with international trade.

Our analysis revealed distinct long-term effects: regarding the direct effects of the different explanatory variables, industrial growth, population growth, trade, and non-renewable energy significantly increased CO_2 emissions, while renewable energy, environmental technology, and geopolitical risk significantly decreased them. Notably, environmental policy stringency had no significant direct impact. Regarding the interaction effects, our interaction analysis demonstrated that both renewable energy and environmental technology can effectively offset the positive influence of trade on CO_2 emissions. This suggests that strategically combining trade with investments in renewable energy and environmental technology offers a promising pathway for mitigating pollution associated with international trade in BRICS nations. However, the interaction between trade and environmental policy does not seem to significantly mitigate the positive effects of trade on CO_2 emissions. Based on these findings, a series of policy recommendations can be implemented to effectively reduce CO_2 emissions and promote sustainable development in BRICS countries. First, enhancing renewable energy adoption is crucial. This can be achieved through strategic investments in renewable energy infrastructure, coupled with targeted financial incentives such as subsidies, feed-in tariffs, and low-interest loans to encourage both production and consumption. Second, supporting research and development in environmental technologies and facilitating international technology transfer will drive innovation. Third, integrating sustainability directly into trade practices is vital. This can involve incorporating robust environmental standards into trade agreements, implementing targeted import taxes or tariffs on energy-intensive goods and actively promoting environmentally sound export initiatives. Fourth, strengthening governance and collaboration is key. This includes fostering inter-sector coordination and encouraging public-private partnerships to leverage expertise and resources effectively. Finally, investing in continuous evaluation of used energy, technologies and trade agreements will ensure that implemented strategies remain effective, adaptable and aligned with evolving sustainability goals. By prioritizing these recommendations, BRICS countries can effectively decouple economic growth from emissions and align trade with environmental sustainability.

Like any research, this study shows interesting results, but it also has limitations that suggest areas for future researchs. First, it would be useful to focus on specific polluting industries to understand their unique impacts on CO_2 emissions. Second, comparing BRICS countries with other emerging economies could help identify effective strategies. Additionally, exploring how trade agreements affect emissions and renewable energy practices is important.

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