Environmental Taxation and Economic Growth: An Analysis on Panel Data ARDL Model, Applied to BRICS Countries

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Abstract

This study investigates the relationship between environmental taxation, economic growth, and CO2 emissions in BRICS countries (Brazil, Russia, India, China, and South Africa) from 1990 to 2021 using the Autoregressive Distributed Lag (ARDL) model. The findings reveal a significant long-term cointegrating relationship among the variables, indicating that economic growth is positively correlated with CO2 emissions, consistent with the Environmental Kuznets Curve (EKC) hypothesis. Specifically, while initial economic growth leads to increased emissions, a turning point is identified beyond which further growth may contribute to emissions reduction. The analysis also highlights the effectiveness of environmental taxation in mitigating CO2 emissions, suggesting that higher tax rates are associated with lower emissions. This underscores the importance of implementing robust fiscal policies to promote sustainable development. The study concludes with policy recommendations aimed at enhancing environmental sustainability while fostering economic growth in BRICS nations, emphasizing the need for a balanced approach that integrates economic and environmental objectives.

Keywords

Environmental Taxation, Economic Growth, CO2 Emissions, BRICS Countries, ARDL Model, Environmental Kuznets Curve

1. Introduction

Climate change represents one of the most pressing environmental challenges of the 21st century, attracting unprecedented global attention over recent decades [1-3]. The significant increase in greenhouse gas (GHG) emissions, primarily driven by the intensive utilization of fossil fuels, has exacerbated this phenomenon, leading to not only climatic disruptions but also substantial economic and social repercussions. Economic literature since the 20th century has underscored the direct impact of environmental degradation on overall economic activity. For instance [4] investigate the relationship between renewable energy utilization and economic growth in BRICS countries, emphasizing the necessity of implementing rigorous environmental policies to reconcile environmental protection with sustainable economic development. These studies highlight the critical role that governments must play in formulating economic strategies that mitigate pollution while sustaining growth trajectories.

Environmental pollution thus emerges as an urgent economic and ecological concern, necessitating appropriate policy responses. A pivotal question arises: can fiscal policies ensure sustained economic growth while simultaneously preserving environmental integrity? Among the public policy instruments considered, carbon pricing has emerged as a vital solution for reducing CO_2 emissions. Specifically, the carbon tax serves as a powerful mechanism for pricing fossil fuels, grounded in the polluter-pays principle, which incentivizes businesses and individuals to adopt more environmentally friendly practices by internalizing the social costs of pollution.

The BRICS nations—Brazil, Russia, India, China, and South Africa—are central to these discussions. As the largest emerging economies and significant contributors to global greenhouse gas emissions, these countries have committed to reducing their carbon footprints while increasing the share of renewable energy in their energy portfolios. However, this dual objective presents considerable challenges due to their heavy reliance on fossil fuels to sustain rapid economic growth.

The impact of carbon taxation has been extensively examined from various perspectives in the literature. Several studies have analyzed the economic implications of carbon taxes [5-10], focusing on their effects on economic growth, employment, and energy costs. Conversely, other studies have compared carbon taxes to alternative mechanisms for reducing CO_2 emissions, such as cap-and-trade systems [11,12], or sought to optimize the design of carbon tax policies to enhance their effectiveness [13-15]. However, the conclusions drawn from these studies often exhibit ambiguity, largely contingent upon the economic contexts of the countries studied, the structure of their energy markets, and the complex interactions between economic variables. This diversity of findings underscores the necessity for specific analyses tailored to each group of countries.

Despite the richness of the existing literature, several gaps persist, particularly concerning the BRICS nations, which are characterized by their geopolitical significance, rapid economic growth, and pivotal role in the global dynamics of CO_2 emissions. Over the past three decades, these countries have experienced remarkable economic growth, with an average annual GDP growth rate of 6.5%. They account for approximately 41.5% of the world's population, 21.5% of global GDP, and possess cumulative foreign exchange reserves exceeding \$4 trillion. However, their dependence on fossil fuels to sustain economic expansion has rendered them substantial emitters of CO_2, exacerbating the global effects of climate change [16,17]. Currently, around 40% of global energy consumption and a significant proportion of global CO_2 emissions are attributed to these nations [1].

The uniqueness of this study lies in its integrated and innovative approach, which aims to simultaneously analyze the impact of carbon taxation on economic growth and well-being in BRICS countries. Unlike previous research that primarily focuses on the economic or environmental effects of carbon taxation in isolation, this study adopts a holistic perspective. It begins with a comprehensive exploration of the relationship between CO_2 emissions and economic growth in BRICS, followed by an examination of the impact of environmental tax policies on these two dimensions. Furthermore, this study considers the institutional specificities of each country by analyzing the role of institutional quality, particularly through variables such as corruption control, in the effectiveness of environmental fiscal policies.

Thus, the objectives of this study are twofold: first, to understand the dynamics between economic growth and CO_2 emissions in BRICS countries, and second, to assess the effectiveness of the carbon tax as a public policy instrument for achieving sustainable economic development. In this regard, this study contributes to the existing literature by providing specific insights into BRICS countries and offering policy recommendations based on robust empirical results.

The remainder of this article is structured as follows: Section 2 presents a literature review, focusing on recent studies addressing environmental policies and carbon taxation. Section 3 describes the data utilized and the methodology employed, with particular attention to the specificities of BRICS countries. Section 4 discusses the empirical results and their implications for policymakers. Finally, Section 5 outlines the conclusions and proposes recommendations for the improved design of environmental policies in BRICS countries.

2. Literature Review

Recent academic discourse has extensively explored the intricate relationship between economic growth and carbon dioxide (CO_2) emissions, positioning it at the core of the global debate on reconciling economic development with environmental sustainability [17,18]. This body of research, while vast, presents a nuanced picture, with findings often depending on geographical context and methodological approach. For instance, studies on emerging economies frequently reveal a strong positive correlation. [19] employed the NARDL approach to analyze India from 1970 to 2018, finding that economic growth significantly contributed to an increase in CO_2 emissions, underscoring India's challenge in decoupling its economic progress from its environmental footprint. Similarly [20] reached a comparable conclusion for South Africa using an ARDL model for the period of 1990 to 2019, suggesting that GDP growth in these nations is tied to a continued reliance on polluting energy sources. This pattern isn't limited to emerging economies; [21] confirmed a similar positive relationship between economic growth and environmental degradation in the United States between 1995 and 2018 using panel data regressions, revealing a recurring pattern where economic expansion tends to exacerbate CO_2 emissions across diverse economic landscapes.

The effectiveness of carbon taxation as a policy tool to mitigate these effects presents a more varied and complex picture. Some research suggests that economic growth can actually drive the implementation of environmental policies. [13] studied Brazil from 1990 to 2018 and found that GDP growth significantly promoted an increase in CO_2 taxation levels, which may indicate a proactive effort by policymakers to offset the negative externalities of growth. A number of researchers agree that environmental taxes can be effective. [7,22-24] all suggest that these taxes incentivize companies to adopt more sustainable practices to avoid financial penalties, leading to an overall reduction in pollution. This is based on the polluter-pays principle, where the social cost of pollution is internalized, making environmentally harmful activities more expensive.

Despite these potential benefits, the implementation of carbon taxes is not without its challenges and drawbacks. [25] argue that the increased operational costs for energy-intensive industries resulting from such taxes can undermine their competitiveness and, in the short term, impede economic growth. Furthermore, companies may pass these costs on to consumers, leading to higher prices and reduced demand. Some scholars have found a more pronounced negative impact, with [26] emphasizing that stringent carbon content taxation can significantly hinder growth, particularly in emerging economies that are still dependent on fossil fuels for development. On a global scale, [27,28] notes that while environmental taxes are effective at reducing emissions, they can also paradoxically stimulate demand and supply for energy-related goods, partially offsetting their intended positive effects.

The nuances of environmental taxation extend to different country contexts. [29] examined the impact of environmental taxes on CO_2 emissions in G7 countries from 1994 to 2014, considering factors like natural resources and economic complexity. Their findings suggest that well-designed environmental taxes can reduce both energy consumption and CO_2 emissions, but they may also put pressure on short-term economic competitiveness. [30], however, contend that appropriately structured tax legislation can redirect production toward less polluting methods, thereby facilitating a transition to a low-carbon economy. For emerging economies like the BRICS nations, the effectiveness of these policies is even more complex. [31] demonstrated the non-linear effects of environmental taxation on CO_2 emissions in these countries, showing that the impact of taxes and technologies varies with the level of globalization. At lower levels of globalization, taxes may surprisingly increase emissions, while at higher levels, they foster reductions by promoting green innovations.

Moreover, the interaction between environmental policies and other economic factors is crucial. [32] used the Quantile Autoregressive Distributed Lag (QARDL) method to analyze the United States, finding that while green growth and innovation have long-term benefits in reducing carbon emissions, their effects vary in intensity depending on the level of growth. This highlights the importance of tailoring fiscal policies to the specific characteristics of each economy. The taxation of natural resources is another key area of research. [11,33] emphasize the role of resource taxes in reducing pollution and sulfur dioxide emissions. [34] even argue that such taxation can help reduce social inequalities by improving income distribution. Nevertheless, [35,36] caution that resource rents can also fuel corruption, underscoring the critical role of institutional quality in ensuring the effectiveness of fiscal policies. Finally, [37] explored the interplay of fiscal and monetary policies, concluding that pollution taxes decrease production and profits but improve overall well-being by reducing emissions. However, restrictive monetary policy can also hinder growth, even as it contributes to pollution reduction. These findings collectively demonstrate that designing economic policies requires a delicate balance between the dual goals of growth and sustainability, and that a one-size-fits-all approach is unlikely to be successful.

3. Data and Methodology

3.1 Data

Panel estimation has been chosen for this study to control for unobserved heterogeneity among BRICS countries and to capture the country-specific characteristics that may influence the relationship between economic growth and CO_2 emissions. This approach also enhances the reliability of the estimates by utilizing a larger sample in terms of time dimension while exploiting the variability across countries. In this regard, emphasizes that the use of panel data helps to overcome issues of individual heterogeneity and yields more robust econometric results.

Our analysis focuses on the five BRICS countries (Brazil, Russia, India, China, and South Africa) over a 32-year period, from 1990 to 2021, generating a panel consisting of 160 observations. The selection of these countries is not arbitrary: they represent approximately 41.5% of the global population and 21.5% of global GDP, while also being among the largest greenhouse gas emitters in the world. Their rapid economic growth is accompanied by significant environmental pressure, which justifies examining the relationship between environmental tax policies and CO_2 emissions in this group of countries. Furthermore, their energy transition and the environmental policies implemented to reduce dependence on fossil fuels make them a relevant case study for analyzing the effects of environmental taxation.

3.2 Methodological Approach : Justification of ARDL

Given the time dimension and the structure of our panel (N=5, T=32), the Autoregressive Distributed Lag (ARDL) approach has been chosen for the analysis. Unlike the GMM estimator, which is more suitable when the number of countries exceeds the time dimension (N > T), ARDL proves to be more appropriate for our case where T > N. Indeed, this method is effective for analyzing long-term relationships and the dynamics of adjustment between variables, even when the data are integrated of different orders (I (0) or I(1)). This allows for modeling the complex interactions between economic growth, environmental taxation, and CO_2 emissions while considering the temporal specificities of each country.

3.3 Sources and Definition of the Data Used

The data used come from various reliable sources recognized for their international coverage and comprehensiveness. The table below presents the selected variables, their definitions, and their sources:

Table 1. Variable, definition and data used

Variable	Definition	Source
CO2	CO2 emissions per capita (in tons)	OWID (2022)
EC	Consumption of primary energies in Kg of oil equivalent per capita	WORLD BANK GROUP (2022)
FBCF	Gross capital formation (% of GDP)	WORLD BANK GROUP (2022)
OUV	The sum of exports and imports denominated by 2 in (% GDP)	WORLD BANK GROUP (2022)
GDP	Gross domestic product per capita constant 2010 in US dollars	OWID (2022)
PRIX	The price of oil per barrel in American dollars	BP Stats Review
RENTE	Natural resource rents as a percentage of GDP	WORLD BANK GROUP (2022)
TAX	Taxe revenue as a percentage of GDP	EUROSTAT

3.4 Méthodologie

To investigate the short- and long-term relationships among taxation, economic growth, and environmental quality in BRICS countries, this study employs the Autoregressive Distributed Lag (ARDL) panel econometric approach, a methodology developed by [38]) and further refined by [39]. This framework is particularly well-suited for long-format panel data where the time dimension (T) exceeds the cross-sectional dimension (N), allowing for the detailed analysis of dynamic adjustments between variables over extended periods. The selection of the ARDL model is justified by its flexibility in handling series integrated of different orders, specifically I(0) and I(1), or a combination thereof [39], which is a common characteristic of macroeconomic time series.

Preliminary Stationarity and Cointegration Analyses

Before the main estimations, it is crucial to assess the stationarity of the time series data. To achieve this, we will perform panel unit root tests using two prominent methods: the [40,41]. The LLC test assumes homogeneity of autoregressive coefficients across all panel units, meaning it presumes a common process governs all countries. In contrast, the IPS test accommodates heterogeneity, allowing for individual-specific autoregressive coefficients. Given the inherent differences in economic structures, institutional frameworks, and energy policies across the BRICS nations, the IPS test provides a more flexible and appropriate approach for our study, as it does not impose the restrictive assumption of a common autoregressive process.

If these unit root tests confirm that the series are non-stationary, we will then conduct a cointegration test to determine if a stable, long-term relationship exists among the variables. For this purpose, we will utilize the [42] cointegration test, which is a robust framework for panel data analysis. This test provides seven distinct statistics—three based on inter-group analysis and four on intra-group analysis—to verify the presence or absence of a cointegrating relationship. A confirmed cointegration relationship would imply that despite short-term fluctuations, the variables move together over the long run, thereby justifying the use of a long-run equilibrium model.

ARDL Panel Model and Estimation Techniques

Once cointegration is established, we will apply the ARDL panel model. This model is especially advantageous for our analysis, which spans 32 years, as it effectively captures both short-term and long-term effects of the explanatory variables on the dependent variable while accounting for potential heterogeneity across countries. To address potential issues such as endogeneity and serial correlation, which are common in cointegrated panels, we will use the Fully Modified Ordinary Least Squares (FMOLS) method. This approach corrects for biases associated with cointegration, thereby enhancing the quality and reliability of the long-run estimates [42]. The FMOLS estimator is particularly valuable for providing a more nuanced understanding of the long-term equilibrium relationships between taxation, economic growth, and CO_2 emissions.

To further refine our analysis and account for varying levels of cross-country heterogeneity, we will also implement several advanced estimation techniques, including the Mean Group (MG) estimator, the Pooled Mean Group (PMG) estimator, and the Dynamic Fixed Effects (DFE) model, as proposed by [38,39]. The MG estimator is the most flexible, allowing for heterogeneous estimation for each country before averaging the results. The PMG estimator, on the other hand, imposes the restriction that the long-term coefficients are uniform across all countries, while allowing for short-term heterogeneity, which is a suitable compromise if the long-run equilibrium relationship is expected to be similar. The DFE model is the most restrictive, imposing fixed coefficients across the entire panel while incorporating country-specific fixed effects to capture unobserved heterogeneity. The choice between these estimators will be guided by statistical tests, such as the Hausman test, to determine the most appropriate model for our specific dataset. The fundamental equation of our ARDL panel model can be expressed as follows:

$$\Delta \ln CO2_{it} = \sum_{j=1}^{p-1} \gamma_{ij} \Delta \ln CO2_{it-1} + \sum_{j=0}^{q} \beta_{ij} \Delta X_{it-1} + \delta_i ((\ln CO2_{it-1}) - \beta_0^i - \beta_1^i X_{it-1} + \varepsilon_{it}$$

With $\ln CO_2$ representing the logarithm of CO_2 emissions per capita, X is a vector that includes all independent variables such as (tax, GDP per capita, energy consumption per capita, energy price, openness rate, gross fixed capital formation, and natural resource rents), β\betaβ are the long-term coefficients, and δi is the speed of adjustment coefficient to the long-term equilibrium. The indices iii and t represent the country and time, respectively.

The model is estimated using three methods: the Pooled Mean Group (PMG) estimator, which constrains the long-term equilibrium to be homogeneous across countries while allowing for heterogeneity in the short-term relationship; the Mean Group (MG) estimator, which accounts for heterogeneity in both the short-term and long-term relationships; and finally, the Dynamic Fixed Effects (DFE) estimator, which constrains the speed of adjustment, the slope coefficient, and the short-term coefficient to show the lack of heterogeneity among countries.

4. Results and inTerpretation

Table 2. Stationarity tests, (Statistical test values with p-values in parentheses)

Variables	TEST I.P. S		TEST L.L.C		TESTA.D. F	
	I (0)	I (1)	I (0)	I (1)	I(0)	I (1)
Ln CO2	-1.598 (0.054)	-4.598 (0.000)	-0.986 (0.162)	-3.986 (0.000)	22.278 (0.013)	
LNEC	-2.233 (0.012)		-2.783 (0.002)		21.304 (0.019)	
LNFCBF	-2.461 (0.006)		-2.313 (0.010)		22.947 (0.010)	
LNOUV	-2.884 (0.002)		-1.416 (0.078)		31.128 (0.000)	
LNGDP	0.067 (0.527)	-5.085 (0.000)	-1.178 (0.147)	10.811 (0.000)	7.247 (0.701)	48.745 (0.000)
LN PRIX	-0.845 (0.199)	-8.915 (0.000)	-1.117 (0.131)	-7.4317 (0.000)	12.719 (0.239)	83.751 (0.000)
LN RENTE	-1.148 (0.125)	-7.668 (0.000)	-0.607 (0.271)	-7.562 (0.000)	12.688 (0.241)	70.623 (0.000)
LN TAX	-0.455 (0.3243)	-4.739 (0.000)	0.201 (0.579)	-4.459 (0.000)	11.255 (0.338)	42.160 (0.000)

Our initial analysis, presented in Table 2, focused on determining the stationarity of the time series data for the variables in our study. The Im, Pesaran, and Shin (IPS) test and the Levin, Lin, and Chu (LLC) test were applied to assess the unit root properties of each series. The results reveal a mixed order of integration among the variables, a common occurrence in macroeconomic datasets. Specifically, variables such as CO_2 emissions, Gross Domestic Product (GDP), oil prices, natural resource rents, and tax revenues were found to be non-stationary at their levels. Their respective p-values were greater than the 5% significance level, failing to reject the null hypothesis of a unit root. However, after taking the first differences of these variables, their p-values dropped significantly below the 5% threshold, leading us to reject the null hypothesis. This confirms that these variables are integrated of order 1, or I(1).

In contrast, other key variables, including primary energy consumption (EC), gross fixed capital formation (FBCF), and trade openness (OUV), demonstrated stationarity at their levels. Their p-values were already below the 5% significance level, indicating that they do not have a unit root. These variables are thus integrated of order 0, or I(0). This heterogeneous mix of I(0) and I(1) variables is a crucial finding, as it directly validates the use of the Panel Autoregressive Distributed Lag (P-ARDL) econometric approach, as developed by [38,39]. This methodology is uniquely suited to handle datasets with variables of different integration orders, which makes it a more flexible and appropriate choice compared to traditional cointegration methods that require all variables to be I(1).

The next logical step in our analysis is to test for the presence of a long-term relationship among these variables. The presence of a long-run equilibrium, or cointegration, is a prerequisite for interpreting the long-run coefficients of an ARDL model. To this end, we conducted the [42] cointegration test, the results of which are presented in Table 3. This test, with its seven distinct statistics based on both intra-group and inter-group analyses, provides a robust framework for determining whether a long-run cointegrating relationship exists among our variables. A positive result from this test would indicate that despite short-term deviations, the variables are bound together by a stable, long-term equilibrium relationship, thereby justifying the estimation of a long-run model. This is a critical step in our study, as it will allow us to assess the long-term dynamics between taxation, economic growth, and environmental quality in the BRICS countries.

Table 3. Pedroni test

	Statistic Prob. Statistic Prob.	Prob.	Statistic	Prob.
Panel v-Statistic	4.128406	0.0000		
Panel rho-Statistic	-2.158626	0.0167	-4.624336	0.0000
Panel PP-Statistic	-4.410684	0.0000	-3.725585	0.0001
Panel ADF-Statistic	-2.160751	0.0154	-3.689700	0.0002

The results of the Pedroni cointegration test, as detailed in Table 3, provide strong evidence for the existence of a stable, long-term equilibrium relationship among the variables under investigation. The test's primary objective is to evaluate the null hypothesis of no cointegration against the alternative that a cointegrating relationship exists within a heterogeneous panel. A key finding is the rejection of the null hypothesis, which is a critical step in justifying the long-run analysis. According to [42], a robust confirmation of cointegration requires two conditions to be met. First, the panel variance should exhibit a high statistical value, and second, the last six of the seven Pedroni test statistics should yield significantly negative values. Our results align perfectly with these criteria. The six relevant statistics are not only negative but are also statistically significant at the 5% level. This is a powerful statistical confirmation that despite short-term fluctuations, the variables—including taxation, economic growth, and environmental quality—are bound together by a stable long-term relationship in the BRICS context.

With the presence of cointegration now established, we can proceed with the Panel Autoregressive Distributed Lag (P-ARDL) approach, a methodology that is expertly suited to model both the short- and long-term dynamics of our variables. To ensure a comprehensive and robust analysis, this study employs three distinct estimation methods: the Pooled Mean Group (PMG), the Mean Group (MG), and the Dynamic Fixed Effects (DFE) model.

Each of these estimators offers a unique perspective on the relationships within the panel. The PMG estimator is a parsimonious approach that assumes the long-run coefficients are homogenous across all BRICS countries while allowing for heterogeneity in the short-run dynamics. This is a reasonable assumption if the underlying long-run equilibrium is expected to be similar across these rapidly developing economies. The MG estimator, in contrast, is more flexible, allowing all coefficients (both short- and long-run) to vary across countries. It estimates a separate ARDL model for each country and then calculates the mean of the coefficients, thus capturing the full extent of cross-country heterogeneity. Finally, the DFE model represents the most restrictive approach, as it imposes homogeneity on both the short- and long-run coefficients across all panel units, while still accounting for unobserved, country-specific effects.

The use of these three estimators is not redundant; rather, it is a strategic choice that enhances the robustness of our findings. By comparing the results from these different models, we can assess the sensitivity of our conclusions to varying assumptions about cross-country heterogeneity. This multi-faceted approach allows for a more nuanced and thorough understanding of the intricate interactions between taxation, economic growth, and environmental quality in the BRICS nations. The results from these models will provide the basis for our discussion of the short- and long-term effects, as well as the policy implications for these economies.

Table 4. Cointegration results (PMG, MG, DE)

D.lnCO2	Coefficient	P>z	Coefficient	P>z	Coefficient	P>z
long-term relationship						
	PMG		MG		DFE	
lnGDP	8.648988	0.005	6.148382	0.0117	.3738405	0.030
lnGDP2	-1.112014	0.007	-0.854206	0.0093	.0771537	0.130
lntax	-.7988262	0.016	0.453124	0.2912	-.0630433	0.025
lntax2	.2682406	0.235	-1.162006	0.0463	.0363898	0.496
lnprix	-.00873	0.567	-0.228721	0.0065	.0106829	0.758
lnEC	.0054872	0.022	-0.238449	0.0182	.3502526	0.000
lnouv	.0173066	0.834	0.556325	0.0030	.2928308	0.002
Ln rente	-.054489	0.094	-0.498037	0.0001	-.0615263	0.026
short-term relationship						
ECT	-.2091794	0.038	-0.103334	0.041	-.2868719	0.000
D1.lnGDP	2.318324	0.045	1.253519	0.0710	-.1622186	0.582
D1.lnGDP2	-.6482083	0.156	1.570774	0.8993	.1097873	0.000
D1.lntax	-.1817704	0.069	0.277884	0.0991	.0636941	0.019
D1.lntax2	.2617905	0.374	-0.196026	0.4273	.0560307	0.000
D1.lnprix	.018278	0.000	0.030344	0.0053	-.013315	0.332
D1.lnEC	.1659297	0.018	0.098900	0.0522	.2525379	0.000
D1.lnouv	.0096363	0.841	-0.076124	0.3146	-.0050604	0.873
D1.lnrente	.000357	0.977	0.023535	0.2264	.0078747	0.731
_cons	-3.078594	0.153	-1.194253	0.1346	-1.010358	0.013
Hausman Test 1			3.92	0.560		
Hausman Test 2			4.18	0.523		
Number of obs	152					
Number of groups	5					

The econometric analysis conducted using PMG, MG, and DFE methods elucidates the structural determinants of per capita CO_2 emissions (in tons) across a panel of countries, simultaneously integrating economic, energy, trade, fiscal, and natural resource-related variables. Long-term results reveal a bell-shaped relationship between real GDP per capita—measured in constant 2010 US dollars—and emissions, consistent with the Environmental Kuznets Curve

(EKC) hypothesis. Specifically, the positive and significant GDP coefficient (PMG: 8.649; $p = 0.005$ / MG: 6.148; $p = 0.012$) reflects rising emissions during early development stages, where industrialization, urbanization, and energy intensity drive growth. Conversely, the negative sign of GDP squared (PMG: −1.112; $p = 0.007$ / MG: −0.854; $p = 0.009$) suggests that beyond an income threshold, this trend reverses: economies shift toward services, environmental standards tighten, and technological innovation enables gradual decoupling of growth from pollution [43-45]. This pattern aligns with [46] conclusion that advanced economies more readily reduce carbon intensity after reaching a development plateau.

Environmental taxation plays a central role. The share of tax revenue in GDP (TAX) exerts a negative and significant effect on emissions in the PMG model (−0.799; $p = 0.016$), illustrating how robust fiscal systems can fund green investments, support clean energy R&D, and implement effective regulations [25,47]. In the MG model, TAX squared is negative and significant (−1.162; $p = 0.046$), suggesting nonlinearity: beyond a certain tax level, incentives for low-carbon behaviors and technologies intensify. This aligns with recent European experiences where eco-taxes exceeding 3% of GDP induced structural emission reductions (OECD, 2023).

Crude oil prices (PRIX), expressed in USD per barrel, show a significant negative impact only in the MG model (−0.229; $p = 0.007$), indicating that price hikes encourage reduced fossil fuel consumption or substitution with cleaner alternatives [48]. However, this effect remains insignificant in PMG and DFE, potentially due to persistent oil dependence in some economies even amid high prices.

Per capita primary energy consumption (EC)—measured in kilograms of oil equivalent—is among the most powerful emission drivers. Coefficients are positive and highly significant across all models, peaking in DFE (0.350; $p < 0.001$), confirming that intensive fossil energy use remains the primary CO_2 emissions source [2,49]. This energy dependency underscores the urgency of transitioning toward renewable-dominated energy mixes.

Trade openness (OUV), measured as the average of exports and imports as a percentage of GDP, exerts a significantly positive effect in MG (0.556; $p = 0.003$) and DFE (0.293; $p = 0.002$). This correlation reflects international trade's amplifying role on industrial production and transportation—two high-emission sectors [50]. Nevertheless, studies note that in advanced economies, openness may also facilitate technology transfers that reduce production carbon intensity [51].

Natural resource rents (RENTE), expressed as a percentage of GDP, emerge as an emission-reducing factor in all three models: PMG (−0.054; $p = 0.094$), MG (−0.498; $p < 0.001$), and DFE (−0.062; $p = 0.026$). This negative relationship may indicate economies reinvesting rents into cleaner infrastructure or substituting fossil fuels with renewables [52]. However, in hydrocarbon-dependent countries, the opposite effect may occur without economic diversification policies.

Short-term dynamics, captured by error correction terms (ECT), are negative and significant across all models (PMG: −0.209; MG: −0.103; DFE: −0.287), indicating reversion to long-term equilibrium aftershocks, with faster adjustment in DFE. At this horizon, GDP per capita exerts an immediate positive effect (PMG: 2.318; $p = 0.045$), while energy consumption retains a robust direct impact. TAX and PRIX effects remain weaker short-term, underscoring that fiscal and price levers require adaptation time to measurably affect emissions.

These results, consistent with recent empirical studies [53,54], advocate for an integrated emission reduction strategy combining environmental taxation, energy transition, regulation of international trade, and sustainable natural resource rent management. Establishing a coherent institutional framework that internalizes environmental externalities while preserving economic competitiveness is essential for reconciling development and sustainability. Ultimately, while empirically validated in our sample, the EKC does not materialize automatically: it demands active policy support and strategic alignment among economic, political, and social actors.

5. Conclusions

This study empirically confirms the validity of the Environmental Kuznets Curve (EKC) hypothesis for BRICS countries, showing that economic growth initially increases per capita CO_2 emissions until reaching an income threshold beyond which emissions tend to decline. However, this transition is neither automatic nor uniform; it heavily depends on the structural characteristics unique to each country, notably their dependence on fossil fuels, institutional capacity, and level of economic development.

The results underscore the crucial importance of well-calibrated environmental fiscal policies, particularly the implementation of differentiated carbon taxes by sector and country, which take into account economic specificities and competitive constraints. For instance, higher taxes on Russian hydrocarbons could coexist with adjusted rates for energy-intensive industries in countries like India, accompanied by targeted compensation mechanisms such as renewable energy training for coal workers or funding for community reforestation projects in the Amazon.

Moreover, phasing out fossil fuel subsidies—which average 2.3% of GDP in BRICS countries—is a priority to free up resources for the modernization of energy grids and the promotion of industrial energy audits that enhance efficiency. Natural resource taxation should also evolve toward a "climate-conditioned" model, whereby higher royalties are applied unless revenues are explicitly reinvested in clean technology research and development.

The trade dimension should not be overlooked: integrating environmental criteria into trade agreements, such as border carbon adjustments or expedited customs clearance for renewable technology imports, is necessary to reduce the carbon footprint associated with trade. The role of multilateral institutions, notably the BRICS Development Bank, is fundamental to accelerate green technology transfers, especially in energy-deficient regions such as certain rural areas in India.

Finally, the success of this ecological transition depends on a transparent, dynamic, and inclusive institutional framework. The creation of a dedicated green fiscal observatory for BRICS, ensuring traceability of environmental tax revenues and sanctioning non-compliance, is a key measure. The recommended policy sequence includes, in the short term, the removal of subsidies and strengthening of efficiency standards, followed in the medium term by the gradual adjustment of carbon taxes accompanied by just transition funds to protect vulnerable populations.

Beyond the empirical validation of the EKC, this study demonstrates that achieving harmonious sustainable development in BRICS countries relies on proactive governance that transcends the traditional trade-offs between economic growth and environmental preservation. Green fiscal policy, combined with intelligent economic diversification and strong stakeholder engagement, must be the cornerstone of an integrated strategy positioning BRICS as global leaders in the low-carbon transition. Representing nearly 40% of global emissions and over 40% of the world population, these countries bear a major ethical responsibility toward future generations. Their innovative policy trajectory will largely determine the success of the global fight against climate change.

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