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SOCIO-ECONOMIC DETERMINANTS OF CO_2 EMISSIONS: EVIDENCE FROM ARDL PANEL DATA ANALYSIS IN BRICS-T COUNTRIES

Abstract

Purpose: This study examines the relationship between carbon dioxide (CO_2) emissions and socioeconomic drivers, including human development (HD), education, financial development (FD), and household consumption for the BRICS-T countries from 2001 to 2022.

Methodology: The study discusses both short- and long-run dynamics while accounting for cross-sectional dependency and heterogeneity across countries by using the panel autoregressive distributed lag (ARDL) model. Data sources include the United Nations and the World Bank hosted databases. Expected years of schooling (EYS) are used as a proxy for educational attainment.

Results: The results indicate significant heterogeneity across the BRICS-T countries. The longrun findings also point to the fact that higher HDI and education levels reduce CO_2 emissions, which shows that sustainable governance and environmental awareness are highly essential for carbon reduction. However, FD has a dual effect, promoting growth as well as carbon-intensive activities. The hypothesis of the environmental Kuznets curve is supported by the findings which indicate that as household consumption structures evolve toward less carbon-intensive activities (reflecting development), there is an associated adjustment toward the long-run equilibrium.

Conclusion: The findings reveal that correction mechanisms are significant for Brazil, India, South Africa, and Türkiye. The study makes a significant contribution to the literature by offering a sophisticated understanding of the socioeconomic factors influencing CO_2 emissions, emphasizing policy directions geared toward sustainable development. The conclusions of this study would be embedded in strategies for striking an appropriate balance between economic growth and environmental sustainability in emerging economies.

Keywords: CO_2 emissions, sustainable development, HDI, panel ARDL analysis, BRICS-T

1. Introduction

Global economic growth, particularly in emerging economies, has been accompanied by environmental challenges, most notably in the form of increasing CO_2 emissions. The BRICST countries of Brazil, Russia, India, China, South Africa, and Türkiye have been very important in this regard, given their rapid industrialization and economic expansion. These countries are among the largest emitters of CO_2 into the atmosphere, largely due to their dependence on fossil fuels and energy-intensive industries (Baloch & Danish, 2022). Economic advances in these nations often involve trade-offs between environmental sustainability and efforts aimed at improving the living standard and rising HD levels.

This turns into a fragile balance where sustainable development requires a simultaneous combination of economic growth, social inclusion, and protection of the environment. In this respect, HDI is a general measure of social and economic development in a country, reflected in health, education, and living standards. While higher HDI levels generally indicate better living conditions, they may also coincide with increased energy use and carbon emissions, making it difficult to achieve environmental sustainability as well (Wang et al., 2019).

Accordingly, education is a vital indicator of HDI, though its role may be complex in this analysis due to e.g. increased ability/requirement for environmental awareness applying sustainable practices. This process may be counterbalanced, as higher educational attainment can make people more economically active, which may result in higher energy-related increased emissions. Understanding the global impact of education on resulting CO_2 emissions will greatly inspire effective policy design (Li & Ullah, 2022).

The other important variable in this matter is FD. A better-developed financial sector could enable investments in clean energy technologies and energy-efficient infrastructure, possibly lowering emissions. At the same time, it may also lead to stimulating industrial activities and increasing consumerism, thereby raising CO_2 emissions. The impact of FD on environmental quality is still under debate (Baloch & Danish, 2022). Similarly, household consumption patterns are crucial drivers of emissions. As income levels rise, consumption tends to increase, but over time, structural changes in preferences and technology can shift consumption toward cleaner and more sustainable goods and services (Wang et al., 2019).

Hence, the present study attempts to examine the influence of socio-economic factors, namely HD and education, on the environmental performance of BRICS-T countries. While economic growth may imply a rise in living standards, it more often than not leads to greater CO_2 emissions due to increased energy use. On the other hand, education can act as a mitigating factor by increasing awareness and promoting more sustainable consumption. In this context, the central research will be conducted based on the effects of HD, education, FD, and household consumption on CO_2 emissions within these countries.

Although each of these factors (independent variables) has been studied individually in relation to its influence on CO_2 emissions, research examining their combined effects is notably scarce, particularly in BRICS-T countries. Given the distinct economic structures and developmental trajectories of these nations, further analysis is necessary to understand how these factors interact and contribute to CO_2 emissions.

This study explores the dynamic interrelationships among HDI, education, FD, household consumption, and CO_2 emissions in BRICS-T countries from 2001 to 2022. By employing a panel ARDL model, the research captures both short-term and long-term effects, offering valuable insights into the relationship between HD and environmental sustainability. This approach distinguishes between the immediate and enduring impacts of development indicators on environmental outcomes, providing crucial guidance for policymakers aiming to balance economic growth with environmental conservation.

The study relies on international datasets from sources such as the United Nations and the World Bank, covering a period marked by significant economic and environmental changes in BRICS-T nations. The findings reveal key patterns. While consumption expenditure and HD reduce emissions in the long run, which is consistent with economic development and sustainability theories, FD increases emissions in the long run. This highlights the carbonintensive nature of industrialization in BRICS-T countries. Education has a significant long-run effect in reducing emissions, indicating the importance of investing in human capital. The relationship between FD and emissions is complex. Empirical evidence suggests that FD has a short-term negative impact on emissions, potentially reflecting the transient investments in green infrastructure. Conversely, HDI indicates a positive effect in the short run, suggesting that initial development stages may still rely on carbon-intensive activities.

The structure of this paper is as follows: Section 2 presents the literature review, which outlines the theoretical framework and examines relevant empirical studies on the connections between development, education, and environmental sustainability, with an emphasis on the BRICS-T countries. Section 3 outlines the methodology employed, provides an overview of the data sources, defines the variables, and details the econometric model used in the analysis. This includes the panel ARDL framework and the rationale for employing PMG and MG estimators. Furthermore, the empirical results are presented, followed by a discussion of the key findings related to the short-term and long-term impacts of HD, education, FD, and household consumption on CO_2 emissions. Finally, the conclusion summarizes the main insights from the study, discusses policy implications, and offers suggestions for future research.

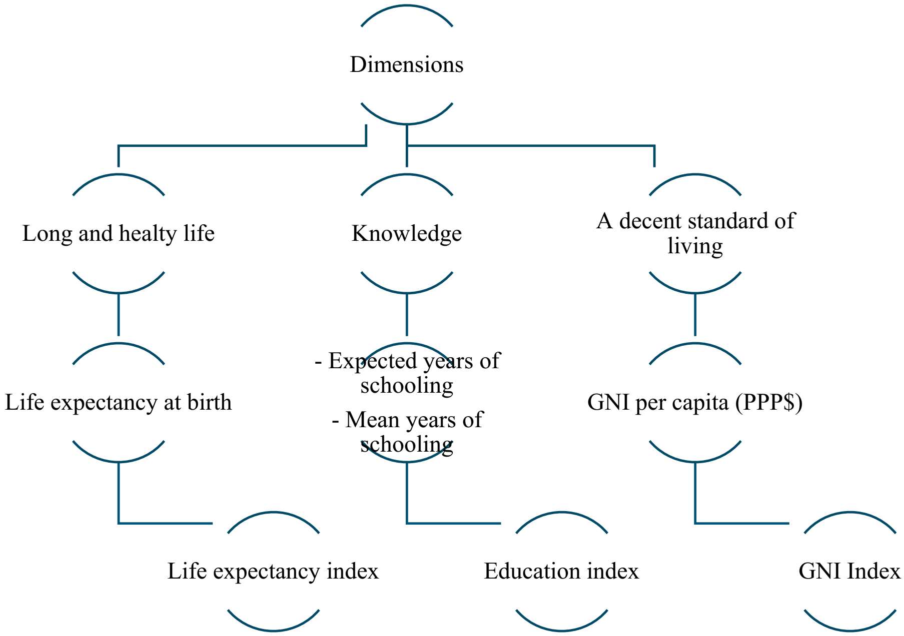
2. Literature review

The environmental consequences of socio-economic development have long been debated within the sustainability literature. This study evaluates the contribution of each of the variables regarding socio-economic development in a univariate approach, i.e., education, HDI, household consumption, and FD, to CO_2 emissions. In other words, this section synthesizes key theoretical and empirical contributions that inform the present study and clarifies how each socio-economic factor interacts with CO_2 emissions in the BRICS-T context.

Education and ecological balance are both necessary for a rich and healthy life (Docrat et al., 2019). The higher the level of education, the more influence there is on behavioral aspects and the more environmentally aware the citizens are, which can also affect carbon emissions. With higher levels of education, environmental consciousness could be raised and the practice of sustainable activity that lowers emissions can be promoted. On the other hand, by promoting industrialization and economic expansion, education may likewise raise emissions. Therefore, the relationship between education and the quality of the ecological environment, including both the direct impact and a mediating role of education, has been shown by current empirical literature (Zhu et al., 2021). Hence, it is widely accepted that education levels directly affect CO_2 emissions including developing and developed countries (Ntanos et al., 2019; Sarwar et al., 2021). For instance, Zhu et al. (2021) state that there is a significant relationship between education level and environmental quality and carbon emissions in China. Similarly, Shobande and Asongu (2022) focus on Eastern and Southern Africa, using third-generation panel unit root and cointegration tests, as well as a panel Granger causality approach. They find that education is a main driver for mitigating carbon emissions. Moreover, Nowotny et al. (2018) point out that sustainability requires development of clean energy technologies; therefore, students' demand for energy education is rising. Yin et al. (2022) evaluated the issue of education within the framework of the COVID-19 period in China. It was concluded that electricity consumption decreased with the increase in online education during that period, and carbon emissions decreased with the elimination of student transportation. Accordingly, Yin et al. (2022) stated that education models are critical to CO_2 reduction and a sustainable environment.

While HD is considered as the process of providing individuals with freedom and opportunities for their well-being, HDI has recently been widely used to measure national well-being and national development (Ahmad et al., 2020; Akbar et al., 2021; Sadiq et al., 2022). In this context, UNDP (2025) points out that "*The HDI was created to emphasize that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone.*" HDI comprises three core dimensions: a long and healthy life, knowledge, and a decent standard of living, as depicted in Figure 1. The three dimensions also include three different indices. These indices are the life expectancy index for the long and healthy life dimension, the education index for knowledge, and the GNI index for a decent standard of living dimension. The life expectancy index is derived from life expectancy at birth, the education index incorporates both expected and mean years of schooling, and the GNI index is based on GNI per capita.

Figure 1 HDI dimensions and indicators



Source: Sen & Anand, 1994

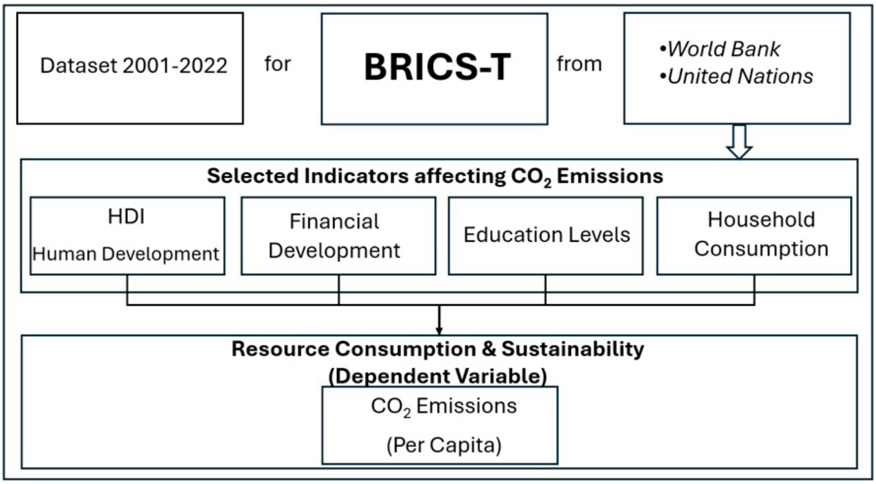
As suggested by Sen and Anand (1994), HDI is a widely utilized economic indicator with a close relationship to industrial development and air quality. For instance, Pervaiz et al. (2021) examine the relationships between HDI and CO_2 emissions in Brazil, China, India, and South Africa, using panel cointegration tests for the 2000Q1–2014Q4 period. Their findings indicate that HDI and CO_2 exhibit a long-term integrated relationship, with HDI having a negative impact on CO_2 emissions. Conversely, other studies have found a robust positive relationship between HDI and carbon emissions. A study conducted by Adekoya et al. (2021) examines the nexus between HDI and CO_2 over the period from 2000 to 2014, focusing on 126 countries. The findings of this study demonstrated a positive relationship between HDI and CO_2 emissions. This observation aligns with the hypothesis that an increase in HDI typically corresponds to an increase in a country's energy consumption and a subsequent rise in CO_2 emissions. However, the relationship is complex and varies across different countries and at different stages of development (Li et al., 2022).

Like many other factors, household consumption is also hypothesized to show a significant role in explaining CO_2 emissions (Zhang et al., 2017). Effective management of household energy demand is essential to achieve carbon neutrality goals. Several studies have addressed this issue; among them, the works of Dai et al. (2012) have performed an analysis of the impacts of household consumption on CO_2 emissions in China for the period 2005–2050. Their findings showed a positive relation between household consumption and CO_2 emissions. Li and Wei (2021) concentrated on China to work out the interactions of household consumption and CO_2 emissions using provincial data from 1995 to 2017. It appeared that a higher rate of household consumption is associated with higher CO_2 emissions. Zhou and Gu (2020) emphasize that reducing emissions from household demand requires optimizing energy use and promoting ecological lifestyles. Finally, Zhang (2013) incorporated input-output analysis with some decomposition techniques and analyzed the induced CO_2 emissions by household consumption in China for the period extending from 1987 to 2007. Results indicate that in urban areas CO_2 emissions are liable to increase on a faster scale compared to those in rural areas on account of ascending consumption. These studies underline that managing consumption behavior can significantly reduce environmental degradation.

The market effect associated with financial crises has gone up, while most scholars have always linked FD with economic growth and development but also pointed out its possible impacts on environmental quality and carbon emissions (Zhang, 2011; Jiang & Ma, 2019). FD, characterized by the expansion of financial markets and institutions, shows a dual impact on carbon emissions. Financial development expands access to credit and investment, which may fund cleaner technologies or, conversely, increase industrial activity and energy use. Acheampong et al. (2020) explored the nexus of financial market development with carbon emissions intensity for 83 countries over the period from 1980 to 2015. In this respect, the study showed that FD, proxied by both market depth and efficiency, is associated with reduced CO_2 emissions for both developed and developing economies. Using province data from 1995 to 2017, Liu et al. (2021) concentrated on China to determine the relationship between FD and CO_2 emissions. Their analysis revealed a positive relationship between FD and CO_2 emissions. Li and Wei (2021) argued that carbon emissions limit the impact of financial and technological development on economic growth. With respect to BRICS countries, Asif et al. (2024) examined the effects of FD, new technologies, economic growth, and trade openness on environmental sustainability. Utilizing data from 2004 to 2023 and employing fixed effect models, the findings indicated that FD has a significant and positive impact on environmental sustainability and CO_2 emissions. In this context, it is suggested that government organizations, in the form of initiatives, must appropriately assess the relationship between FD and emission reduction.

This comprehensive synthesis provides the foundation for understanding the conceptual framework of this research, as illustrated in Figure 2.

Figure 2 Conceptual framework of the study



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3. *Methodology*

This paper employs an extensive econometric analysis to investigate the level of CO_2 emissions in relation to a number of socio-economic and financial variables such as HDI, levels of education, FD, and household consumption for the BRICS-T economies over the period 2001–2022. The estimation method adopts a panel ARDL approach, which accommodates heterogeneity and cross-section dependence between countries, with the objective of jointly outlining both short-run dynamics and long-run equilibrium relationships.

For clarity and consistency, a unified set of terms and symbols is adopted throughout the paper, and measurement units are reported alongside all estimates. Table 1 is provided to define each variable together with its measurement unit and data source. ARDL coefficients are interpreted with respect to these units (e.g., CO_2 in metric tons per capita; education in years; consumption as % of GDP). Estimator abbreviations (PMG, MG, DFE) are introduced once and then used uniformly, and units are indicated in every results table so that magnitudes and signs can be read unambiguously. In this way, the meaning of each symbol and the interpretation of each coefficient are made transparent at a glance.

Table 1 Definitions of variables

Abbr.	Variable Description	Measurement Unit	Source
CO_2	Carbon dioxide emissions per capita	Metric tons per capita	World Bank (WDI)
HDI	Human Development Index	Index (0–1 scale)	UNDP Human Development Reports
EDU	Education (Expected years of schooling)	Years	UNDP Human Development Reports
FD	Financial Development Index	Composite index (normalized)	IMF & World Bank Global Financial Development Database
CONS	Final household consumption expenditure	% of GDP	World Bank (WDI)
ECT	Error correction term	Coefficient (unitless)	Derived from the ARDL model

Source: Created by authors

The model utilizes several econometric tests and models for the robustness of results. The initial step involves the implementation of tests to assess the presence of cross-sectional dependence. The interdependence of countries within the panel is determined through the application of three distinct tests; the Breusch-Pagan LM test by Breusch and Pagan (1980), the scaled LM test by Pesaran (2004), and the CD test by Pesaran et al. (2008) are used to find out the interdependence of countries within the panel. Secondly, slope homogeneity tests are conducted. The Hsiao test is conducted in order to determine whether slope coefficients are homogeneous across countries (Hsiao, 1986). The third step involves the application of panel unit root tests. Initially, the ADF-Fisher-type test proposed by Maddala and Wu (1999) is employed. Subsequently, the PP-Fisher-type test, presented by (Choi, 2001), is utilized to determine the order of integration of the series.

In the present study, after applying preliminary tests and stationarity analysis, cointegration analysis was further applied. The long-term relationship among the variables has been detected by using the Pedroni cointegration tests (Pedroni, 1999; 2004), the Kao test (Kao, 1999), and the Johansen Fisher panel cointegration test. The latter is a combination of Johansen's cointegration test (Johansen, 1988; 1991) and Fisher's (1928) combined test. It involves the application of Johansen's methodology in the context of panel data using Fisher type aggregation techniques. It is applied and refined by prominent econometricians including Maddala and Wu (1999) and Pedroni (1999). The panel ARDL model is estimated using the Pooled Mean Group (PMG) estimator and the Mean Group (MG) estimator proposed by Pesaran et al. (1999). The primary advantage of the PMG estimator is that it constrains the assumption of homogeneity across countries with regard to long-run coefficients, while allowing for heterogeneity in the short run. In contrast, the MG estimator allows for heterogeneity in both short- and long-run coefficients. The Hausman test is conducted to determine the best model specification. The error correction term in the panel ARDL model is utilized to determine the speed of adjustment toward longrun equilibrium. The panel ARDL model is expressed as:

$$\Delta Y_{i,t} = \alpha_i + \sum_{j=1}^{p} \beta_{i,j} \Delta Y_{i,t-j} + \sum_{j=1}^{p} \gamma_{ik} \Delta X_{i,t-k} + \lambda_i \left(Y_{i,t-1} - \phi_i \Delta X_{i,t-1} \right) + \varepsilon_{i,t}.$$

In the model, the dependent variable (CO_2 emissions) for country i at time t is represented by $\gamma_{i,t}$, while the independent variables (HDI, EYS, FIN_DEV, CON_EXP_GDP) are represented by $X_{i,t}$. Additionally, the model incorporates country-specific effects (α_i), short-run coefficients ($\beta_{i,j}$, $\gamma_{i,k}$), long-run coefficients for independent variables (φ_i), speed of adjustment parameters (λ_i), and error terms ($\varepsilon_{i,t}$).

The error correction model is formulated as:

$$\Delta Y_{i,t} = \propto_i + \sum_{j=1}^{p-1} \beta_{i,j} \Delta Y_{i,t-j} + \sum_{j=1}^{q-1} \gamma_{ik} \Delta X_{i,t-k} + \lambda_i COINTEG_{i,t-1} + \varepsilon_{i,t},$$

where $COINTEQ_{i,t} = Y_{i,t} - \phi_i X_{i,t-1}$ is the error correction term. λ_i is expected to be a negative and statistically significant value.

Panel ARDL analysis can deal with mixed-integration-order variables, including I(0) and I(1). Thus, both the short- and long-run dynamics are estimated within a single framework. The estimation method also permits heterogeneity across countries, which is highly valued for drawing accurate policy implications. Such a robust analysis will ensure that the levels of CO_2 emissions are pursued with value-added insight into the individual and collective dynamics of the BRICS-T countries.

4. Results and findings

This study examines the impact of HDI, education, FD, and household consumption on the CO_2 emissions of the BRICS-T countries from 2001 to 2022. The time period under examination is selected on the basis of data availability. Data on HDI and education levels are gathered from the United Nations database, while FD and household consumption data are sourced from the World Bank database. Expected years of schooling (EYS) is employed as a proxy for educational achievement. A panel Autoregressive Distributed Lag (ARDL) model is constructed using the aforementioned data, incorporating both pooled mean group (PMG) and mean group (MG) approaches to analyze long-term and short-term dynamics.

The initial preliminary tests entail the examination of cross-sectional dependence among the countries within the panel, and the assessment of homogeneity of the slope coefficient in the long-run equation. The notion that the individual units are independent represents a significant challenge that inevitably arises in the context of panel data analysis. This issue has the potential to influence the estimation of parameters and the interpretation of inferences. The concept of "between-group" dependence has been a prominent feature of social sciences since the 1930s, a considerable period preceding the advent of panel data econometrics (Sarafidis & Wansbeek, 2012). In this context, the term "cross-sectional dependence" is used to indicate whether there is inter-country dependency.

Table 2 Cross-sectional dependence and homogeneity tests

Test	Statistic	Prob.
Breusch-Pagan LM	14.05541	0.5213
Pesaran scaled LM	-0.172458	0.8631
Bias-corrected scaled LM	-0.339125	0.7345
Pesaran CD	-0.15406	0.8776
Specification Tests of Hsiao (1986)		
Hypotheses	F-Stat	
H1	557.7847	6.93E-93
H2	16.08071	2.04E-22
H3	756.8078	9.39E-87
"H1 = Null Hypothesis : Panel is homogeneous vs Alternative Hypothesis : H2"		
"H2 = Null Hypothesis : H3 vs Alternative Hypothesis : Panel is heterogeneous"		
"H3 = Null Hypothesis : Panel is homogeneous vs Alternative Hypothesis : Panel is partially homogeneous"		

Source: Created by authors

As demonstrated in Table 2, all four tests consistently indicate the absence of cross-sectional dependence, as evidenced by p-values exceeding 0.05. This result fails to reject the null hypothesis, which suggests the absence of cross-sectional dependence. This suggests that the countries included in the analysis are sufficiently independent with respect to their residuals. Furthermore, the test results point out that there is no evidence of a correlation between countries' unobserved factors and CO_2 emissions. To test for heteroskedasticity, the White (1980) test is employed. The nR^2 statistic is calculated using the squared residuals as the dependent variable and compared with the critical values of the chi-square distribution. The results demonstrate that there is no evidence of heteroscedasticity.

In view of these diagnostics, the use of first-generation unit root tests that assume crosssectional independence is warranted, and slope heterogeneity is addressed explicitly at the estimation stage. Moreover, the panel ARDL framework with an error-correction representation (Pesaran et al., 1999) helps to mitigate endogeneity and omitted-variable concerns by capturing dynamic feedback through lags and by conditioning on the long-run relationship. Autocorrelation is likewise handled by the lag structure (selected via Akaike information criteria (AIC)) and by the negative, statistically significant error-correction term reported below. This sequence—cross-sectional checks, unit-root testing under independence (Choi, 2001; Maddala & Wu, 1999), multiple cointegration tests, and ARDL-ECM estimation—follows established practice for panel settings where cross-sectional dependence is not detected (Sarafidis & Wansbeek, 2012).

The Hsiao test indicates that the slope coefficients in the model are not homogeneous. In light of the outcomes of the cross-sectional dependence and homogeneity tests, the subsequent phase of panel data analysis will utilize first-generation unit root tests that assume heterogeneity while accounting for cross-sectional independence.

Table 3 Unit root tests

Variables/Tests	ADF – Fisher Chi-square	PP – Fisher Chi-square	
D(CO2)	67.7462a (0.0000)	5.4063a (0.0000)	I(1)
D(HDI)	19.5251a (0.0766)	34.1929a (0.0006)	I(1)
D(EYS)	51.4709a (0.0000)	67.0123a (0.0000)	I(1)
FIN_DEV	23.6636b (0.0226)	13.9281b (0.3053)	
D(FIN_DEV)	33.9528a (0.0007)	3.7194a (0.0000)	I(1)
CON_EXP_GDP	28.9744b (0.0040)	18.3921b (0.1043)	
D(CON_EXP_GDP)		76.6779a (0.0000)	I(1)

Note: The numbers in parentheses are the probability values related to unit root tests. Δ is a processor indicating that the first differences of variables are taken. The Schwarz information criterion has been used to determine the optimal delay number. a: none, b: constant.
Source: Created by authors

The variables CO_2 emissions, HDI, expected years of schooling, consumer expenditures in GDP, and FD are stationary at the first difference, as indicated by the first-generation unit root tests (Table 3).

In the subsequent phase of the analysis, the cointegration relationship between the variables is investigated through the use of the Pedroni cointegration test, the Kao test, and the Johansen Fisher test. The results of the aforementioned tests are presented in Table 4.

Table 4 Cointegration tests

Test	Statistic	Prob.	Null Hypothesis	Conclusion
Pedroni Test (withindimension)			No cointegration	Mixed evidence
Panel v-Statistic	-1.236952	0.8919	Fail to reject	No cointegration
Panel rho-Statistic	1.638319	0.9493	Fail to reject	No cointegration
Panel PP-Statistic	-1.810399	0.0351	Reject	Evidence of cointegration
Panel ADF-Statistic	-0.9535	0.1702	Fail to reject	No cointegration
Pedroni Test (betweendimension)			No cointegration	Mixed evidence
Group rho-Statistic	1.87848	0.9698	Fail to reject	No cointegration
Group PP-Statistic	-2.272901	0.0115	Reject	Evidence of cointegration
Group ADF-Statistic	0.543444	0.7066	Fail to reject	No cointegration

Test	Statistic	Prob.	Null Hypothesis	Conclusion
Kao Test	ADF	-1.202181	0.1146	Fail to reject
Johansen Fisher Test			No cointegration	Strong evidence of cointegration at multiple ranks
None	246.6 (Trace), 141.1 (Max)	0	Reject	Strong evidence of cointegration
At most 1	163.6 (Trace), 80.25 (Max)	0	Reject	Strong evidence of cointegration
At most 2	102.6 (Trace), 43.87 (Max)	0	Reject	Strong evidence of cointegration
At most 3	78.23 (Trace), 53.73 (Max)	0	Reject	Strong evidence of cointegration
At most 4	54.36 (Trace), 54.36 (Max)	0	Reject	Strong evidence of cointegration

Source: Created by authors

The application of the Pedroni, Kao, and Johansson Fisher tests to the dataset enables the identification of subtle insights into the existence of cointegration across countries. The Pedroni test, which accounts for cross-sectional heterogeneity, yields inconclusive results, with the Panel PP and Group PP statistics indicating evidence of cointegration. In contrast, the Kao test, which assumes homogeneity, is unable to detect cointegration. The Johansen Fisher test offers most compelling evidence, consistently rejecting the null hypothesis of no cointegration at all hypothesized ranks. However, it does not explicitly address heterogeneity. Overall, the evidence suggests the presence of a cointegrating relationship among the variables.

The subsequent step is to estimate the ARDL model proposed by Pesaran et al. (1999). This model assumes a long-run relationship among the variables, following the establishment of cointegration. In this study, the ARDL (1,1,2,1,1) model is selected based on the AIC, which ensures an optimal balance between model complexity and explanatory power. Table 5 presents the estimated coefficients for both the pooled mean group (PMG) and the mean group (MG) models, which capture the dynamics of the relationships in both the short run and the long run.

Table 5 PMG and MG model coefficients

Variable	Pooled Mean Group (PMG)			Mean Group (MG)		
	Coefficient	t-Statistic	Prob.	Coefficient	t-Statistic	Prob.
Long-run Coefficients						
CON_EXP_GDP	-0.096265	-4.879918	0.0000	-0.003474	-0.067565	0.9463
EYS	-0.111808	-2.07342	0.0405	0.507005	0.61673	0.5388
FIN_DEV	0.059324	14.22425	0.0000	0.02944	1.701075	0.0921
HDI	-9.023453	-4.828372	0.0000	-17.97303	-0.987344	0.3259
Short-run (Mean-Group) Coefficients						
COINTEQ	-0.416667	-2.341926	0.021	-0.892343	-4.120264	0.0001
D(CON_EXP_GDP)	0.03032	0.567481	0.5716	0.006248	0.39625	0.6928
D(EYS)	-0.285124	-0.954778	0.3418	-0.398255	-1.070567	0.287
D(EYS(-1))	0.284379	1.999714	0.0481	-0.068689	-0.238742	0.8118
D(FIN_DEV)	-0.021511	-3.551505	0.0006	-0.030855	-2.130643	0.0356
D(HDI)	19.23082	2.479104	0.0147	11.16962	1.179206	0.2412
C	7.836227	2.23872	0.0272	6.485917	2.104959	0.0379

Source: Created by authors

In order to ascertain which of the PMG and MG models is superior, a Hausman test is employed. The results are exhibited in Table 6. In the context of the Hausman test, the null hypothesis states that the PMG model is preferred. The results of the test indicate a statistically significant difference between the PMG and MG estimators (P-value < 0.05). Therefore, the MG estimator is preferable over the PMG estimator. However, the PMG estimator is statistically similar to the Dynamic Fixed Effect (DFE) estimator, indicating that PMG is a superior alternative to DFE. Given that PMG is designed to handle heterogeneity in short-run dynamics across countries (a crucial consideration for BRICS-T nations with diverse economic profiles), and that it is not rejected against DFE, the PMG estimator is the preferred option for the analysis.

Table 6 PMG Hausman specification test

Estimator	Stat.	p-Value
Mean Group	38.082977	0.0000
Dynamic Fixed Effects	4.943653	0.2931

Source: Created by authors

In the PMG model, all long-run coefficients are statistically significant. Consequently, a oneunit increase in consumption expenditure as a percentage of GDP leads to a reduction in CO_2 emissions by 0.0963 units in the long run. This finding is consistent with the environmental Kuznets curve hypothesis (1955), which suggests that as consumption increases, BRICS-T countries transition toward less carbon-intensive consumption patterns. A one-unit increase in educational attainment reduces CO_2 emissions by 0.1118 units in the long run. It seems reasonable to posit that improvements in education enhance environmental awareness across BRICS-T countries. A one-unit increase in FD is associated with a 0.0593 unit increase in CO_2 emissions in the long run. In BRICS-T countries, FD appears to support industrial expansion and infrastructure development, which are often carbon-intensive. A one-unit increase in HDI reduces CO_2 emissions by 9.0235 units in the long run. Higher HD often coincides with better governance, improved energy efficiency, and adoption of cleaner technologies, which collectively contribute to a reduction in emissions.

The COINTEQ coefficient is negative and statistically significant, indicating that approximately 41.67% of deviations from the long-run equilibrium are corrected annually. This adjustment process is relatively rapid, with BRICS-T countries reaching long-run equilibrium within a few years (approximately 2.4 years). The coefficients for FD and education are significant in the short run. A one-unit short-term increase in FD reduces emissions by 0.0215 units. This is in contrast with the long-run effect, which suggests that short-run financial flows may support low-carbon investments or temporary shifts in economic activity. Short-term changes in HDI are associated with an increase in carbon emissions by 19.2308. This may reflect the initial growth effects of development, where increasing HDI in the short term often accompanies carbon-intensive activities.

Table 7 Bounds tests

Bounds Test for Levels Relationship			
Country	**F-Stat.**	**t-Stat.**	**Decision on Cointegration**
Türkiye	5.276192	-3.321853	Weak evidence at 10% level
Brazil	18.62785	-5.010737	Strong evidence (1% level)
Russia	1.880167	-1.632892	No evidence
India	8.543802	-4.246945	Strong evidence (1% level)
China	4.125407	-0.771953	No evidence
South Africa	9.501309	-5.602375	Strong evidence (1% level)

Source: Created by authors

This study employs an ARDL bounds testing approach to investigate the existence of a levels relationship among variables across six countries. The null hypothesis of “no levels relationship” is evaluated through the use of F-statistics and t-statistics for each country. The results are then compared against the critical values for all series that are found to be stationary at level I(1). The findings are presented in Table 7. For Brazil, India, and South Africa, the Fstatistics exceed the upper bound critical values at all levels of significance, providing substantial evidence for rejecting the null hypothesis and indicating cointegration. In the case of Türkiye, the F-statistic exceeds the critical value at the 10% significance level, but not at the 5% level, indicating that the evidence of cointegration is weak. F-statistics for Russia and China are below the critical value bounds, failing to reject the null hypothesis. The t-statistics yield analogous results. The sole distinction is that the t-statistic for Türkiye fails to provide evidence of cointegration. The error correction term is negative and statistically significant for Türkiye, Brazil, India, and South Africa, confirming the adjustment toward long-run equilibrium as illustrated in Table 8.

Table 8 Error correction coefficients

Short-Run and Long-Run Coefficients (Key Variables)				
Country	**Variable**	**Coefficient**	**t-Stat.**	**Prob.**
Türkiye	**COINTEQ**	**-0.90823**	**-5.438181**	**0.0002**
D(FIN_DEV)	-0.036472	-3.160329	0.0082	
Brazil	**COINTEQ**	**-0.243954**	**-7.239694**	**0.0000**
D(CON_EXP_GDP)	-0.037754	-5.369192	0.0002	
Russia	COINTEQ	-0.2057	-1.121642	0.284
D(CON_EXP_GDP)	-0.079471	-2.87707	0.0139	
India	**COINTEQ**	**-0.056116**	**-2.469494**	**0.0295**
D(FIN_DEV)	-0.020938	-3.727341	0.0029	
China	COINTEQ	-0.057336	-0.702653	0.4957
D(EYS)	-1.663139	-1.679436	0.1189	
South Africa	**COINTEQ**	**-1.028663**	**-6.830662**	**0.0000**
D(CON_EXP_GDP)	0.284438	3.917386	0.002	

Source: Created by authors

In conclusion, the results provide strong evidence of cointegration for Brazil, India, and South Africa, as evidenced by both the F-statistics and the error correction terms. In contrast, T**ü**rkiye exhibits only weak evidence of cointegration, while Russia and China fail to demonstrate any significant levels relationship. These findings highlight the varying long-run dynamics across countries, emphasizing the heterogeneity in the relationship between economic variables and environmental or development indicators.

5. Discussion and conclusion

The present study focuses on the cointegration analysis between HDI, education, FD, household consumption, and CO_2 emissions for the BRICS-T countries over the 2001–2022 period. Utilizing panel ARDL models, this study provides both general and country-specific aspects related to the long- and short-run dynamics of these associations.

The findings reveal strong heterogeneity across the countries analyzed. While substantial evidence of cointegration is observed for Brazil, India, and South Africa, indicating the presence of a stable long-run relationship between the variables in these countries, the evidence for Türkiye is comparatively weak, and no significant relationship is observed in the case of Russia and China. Such variation underlines the fact that BRICS-T countries are at different stages of development and, consequently, possess distinct policy environments.

The long-run results show that improvements in education and HD significantly reduce CO_2 emissions. This confirms the view that higher HDI levels and greater environmental awareness promote sustainability through better governance and cleaner technologies. However, FD presents a mixed effect. It supports growth and infrastructure development but also increases carbon-intensive activities, especially in rapidly industrializing economies like those of the BRICS-T.

Household consumption also plays a complex role. The study finds a negative long-run relationship between consumption expenditure and emissions, which aligns with the Environmental Kuznets Curve hypothesis. As countries advance, consumption patterns shift toward less carbon-intensive goods and services, contributing to lower emissions in the long term.

A deeper examination of the short-run results of the study reveals the presence of rapid adjustment mechanisms within the BRICS-T countries. The COINTEQ coefficient suggests that deviations from equilibrium are relatively quickly corrected, especially for Brazil, India, South Africa, and Türkiye. The short-run dynamics reflect transitional economic activities that may lead to temporary emission increases, as evidenced by changes in HDI.

To contextualize the short-run HDI result, note that HDI is scaled 0–1 and annual changes are typically small. Under the PMG estimate reported in Table 5 ($\Delta HDI \approx 19.23$, $p < 0.05$), a 0.01 increase in HDI implies an increase of about 0.19 tons of CO_2 per capita in the short run (19.23×0.01). This magnitude is therefore moderate and consistent with transitional dynamics: rapid improvements in health, schooling, and income can temporarily raise energy use before efficiency gains and cleaner technologies diffuse. This interpretation is also consistent with our negative long-run HDI coefficient, which indicates that higher HD ultimately aligns with lower emissions; similar short-run/long-run contrasts are reported in peer-reviewed studies on human development/human capital and emissions in emerging economies (Adekoya et al., 2021; Wang et al., 2019).

The findings of this study are consistent with previous research in the literature. For example, Zhu et al. (2021) and Shobande and Asongu (2022) report a positive role of education in emissions reduction. The bidirectional effect of FD also supports the findings of Acheampong et al. (2021) and Liu et al. (2021). However, the observed heterogeneity among BRICS-T countries highlights the importance of incorporating regional and country-specific factors into policy design for sustainable development.

The study emphasizes that achieving balanced economic growth with environmental sustainability necessitates customized strategies with policy interventions prioritizing investments in education, sustainable financial systems, and clean technologies, while promoting consumption patterns aligned with carbon neutrality goals. The findings provide valuable insights for policymakers and researchers who aim to address the pressing challenges posed by climate change in emerging economies. In this regard, the importance of education should be highlighted, as it is crucial for achieving long-term emissions reductions by fostering environmental awareness and green innovations. HD initiatives must incorporate low-carbon measures, and long-term policies should aim to redirect FD toward sustainable practices that impact carbon emissions.

This study relies on the best available annual data for BRICS-T (2001–2022); some institutional or technology variables could not be observed directly. These are the primary limitations of research. The dynamic ARDL–ECM design and diagnostic sequence help mitigate simultaneity, autocorrelation, and spurious long-run inference, but endogeneity cannot be ruled out entirely (Pesaran et al., 1999). Cross-sectional dependence was not detected in our sample; nonetheless, time-varying common shocks remain a general caveat (Sarafidis & Wansbeek, 2012). These points do not alter the main conclusions but mark natural directions for future work, e.g., testing structural breaks when longer series are available or exploring instrumented estimators as additional sensitivity. Future research could include additional socio-economic variables and extend the inquiry to other developing regions to gain a more comprehensive understanding of these dynamics.

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