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Determinants of environmental sustainability transitions in BRICS economies: Evidence from policy stringency, globalization, eco-innovation and democratic institutions

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ABSTRACT

Environmental degradation remains a significant challenge for emerging economies, particularly in the BRICS countries Brazil, Russia, India, China and South Africa where rapid economic growth, globalization and institutional transitions continue to intensify pressure on ecological systems. This study investigates the dynamic relationship between ecological footprint and key economic, institutional and policy related factors, including gross domestic product, globalization, environmental technology as a proxy for eco innovation, environmental policy stringency and democracy. To address a gap in the existing literature, which has largely relied on mean based estimation techniques, this study applies the Method of Moments Quantile Regression to examine how these relationships vary across different levels of environmental pressure in BRICS countries during the period 1996 to 2022. The results indicate that GDP, globalization and democracy significantly increase environmental degradation across all quantiles. By contrast, environmental policy stringency and green technology contribute to reducing environmental degradation, particularly at higher pollution levels. The findings obtained from Fully Modified Ordinary Least Squares and Dynamic Ordinary Least Squares are consistent with the quantile regression results, confirming the robustness of the analysis. In addition, the Dumitrescu Hurlin causality test reveals unidirectional causality running from ecological footprint to GDP and environmental technology, while bidirectional causality is identified between ecological footprint and environmental policy stringency and between ecological footprint and democracy. Overall, the findings provide important policy insights for BRICS countries by emphasizing the need for targeted and flexible strategies that balance economic development with environmental sustainability.

1. Introduction

In recent decades, environmental issues have attracted increasing attention at the global level. Policy strategies aimed at reducing CO_2 and other greenhouse gas (GHG) emissions have placed growing emphasis on public awareness campaigns, carbon taxation, innovation promotion and the rapid adoption of renewable energy technologies [1,2]. As environmental crises have intensified worldwide, ecological challenges have become a central concern in both academic research and policy formulation [3,4]. Within this context, the BRICS countries have experienced substantial economic expansion and structural transformation in recent years [5]. However, this rapid development has also made them responsible for almost 40% of global energy consumption and a considerable share of global CO_2 emissions [1,6].

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Nevertheless, CO_2 emissions alone do not provide a complete assessment of environmental degradation because they fail to capture pressures on forests, fisheries, minerals, soil and other natural resources. By contrast, the ecological footprint (EFP), introduced by Wackernagel and Rees [7], provides a broader indicator of the overall environmental burden generated by human activity [8]. As the BRICS economies continue to grow, they face increasingly serious ecological challenges that require urgent and coordinated policy responses. Against this background, this study addresses the following research question: How do institutional, economic and technological factors influence the ecological footprint, as a broader and more comprehensive measure of environmental sustainability than conventional emissions based indicators?

Globalization refers to the growing interconnectedness of countries through trade in goods and services, capital flows, financial integration, technology transfer and information exchange [9]. Through these channels, globalization significantly influences economic, social and political systems [10]. From a theoretical perspective, globalization may affect the ecological footprint in different ways and may generate both positive and negative environmental outcomes. On the one hand, economic globalization can facilitate technology transfer and the diffusion of innovation, enabling cleaner production methods and broader use of renewable energy, which may reduce resource depletion and emissions [11]. Its social and political dimensions can also support international environmental standards, increase awareness and encourage sustainability oriented behavior [12,13]. On the other hand, globalization may increase ecological pressure through scale, composition and technique effects, particularly when pollution intensive industries expand or inefficient technologies remain in use [11,14]. These dynamics can intensify biodiversity loss, resource overuse and environmental stress beyond natural carrying capacities. Previous studies confirm this dual effect, showing that globalization can improve environmental efficiency in developed economies while strengthening pollution haven effects in emerging economies such as the BRICS countries [15]. In this context, eco innovation, reflected through environmentally related technologies, plays an important role in reducing CO_2 emissions and supporting sustainable development by aligning economic growth with long term resource conservation [16].

Environmental policy stringency (EPS) refers to the degree to which regulations, taxes and standards are designed to reduce environmental damage, including emission limits, carbon pricing instruments and energy efficiency requirements [17]. These measures influence the behavior of firms and consumers and can encourage more sustainable production and consumption patterns [18]. Theoretically, EPS affects the ecological footprint mainly through enforcement and incentive mechanisms. Stricter environmental policies can encourage clean innovation, improve resource efficiency and accelerate the transition toward low carbon development, thereby reducing pressure on land, water, biodiversity and other dimensions of ecological sustainability [18]. However, strict environmental policies may also create short term adjustment costs or become less effective in countries where institutional enforcement is weak. In such contexts, they may lead to rebound effects or the relocation of polluting activities. Previous research points to this mixed pattern. While EPS has contributed to sustainability improvements in advanced economies, its effectiveness in emerging markets such as BRICS often depends on institutional quality and regulatory capacity [19].

Democracy is another important institutional factor shaping environmental outcomes. Through participatory governance, access to information and electoral accountability, democratic systems influence public demand for environmental protection and the policy responses of governments [16]. On the positive side, democracy can improve transparency in environmental performance, strengthen public pressure for conservation and support the adoption of stricter regulations and environmentally responsible practices [20]. However, in fragile or unstable democratic systems, short term electoral interests may encourage policymakers to prioritize economic expansion over environmental protection, which can delay reforms or weaken enforcement [21]. Existing studies reflect this duality and suggest that stronger democratic institutions are often associated with lower ecological footprints in emerging economies, although this effect depends strongly on complementary conditions such as policy stringency and institutional quality [21]. Overall, robust democratic institutions can strengthen sustainable development by helping to align economic progress with ecological limits.

The selection of the BRICS countries as the sample for this study is justified for several reasons. First, their large and rapidly growing populations intensify demand for natural resources and energy, thereby directly contributing to the expansion of the ecological footprint [10]. Second, these economies collectively account for approximately 21% of global GDP [22] and have experienced rapid industrialization. They are therefore major drivers of global economic growth but also major sources of environmental pressure, including high greenhouse gas emissions and resource depletion [5]. As some of the world's largest emitters, the extent to which environmental policy stringency, globalization, eco innovation and democratic institutions can shape sustainable transitions in the BRICS countries has important implications for global climate objectives [23]. Third, the diversity of BRICS countries in terms of political systems, economic structures and institutional conditions provides a valuable comparative setting for examining how these factors influence the ecological footprint across different levels of environmental pressure. Unlike many developed economies that are locked into high emission infrastructure, BRICS countries may have greater potential to leapfrog traditional development pathways by adopting cleaner technologies at earlier stages. Their institutional diversity also offers useful insights into how governance quality affects environmental policy enforcement and long term ecological sustainability.

This study contributes to the literature in several important ways. First, it addresses key research gaps concerning sustainable transitions in emerging economies, particularly in the BRICS context. Previous studies have mainly used CO_2 emissions, GHG emissions or PM2.5 concentrations as proxies for environmental degradation and have paid less attention to broader biocapacity based measures and to the combined influence of institutional, economic and technological factors [2,6,24]. By using the ecological footprint as a more comprehensive indicator of sustainable transitions, covering land, water and resource demands, this study provides a broader and more nuanced assessment of environmental pressure. Second, unlike earlier studies that mainly rely on mean based models, this research applies the Method of Moments Quantile Regression (MM QR), which better accounts for endogeneity, heterogeneity across quantiles and location, individual and time effects. This allows for a more robust analysis of how the selected variables affect ecological pressure at different levels over the period 1996 to 2022. Third, by adopting a comparative perspective across diverse BRICS political economies rather than relying on single country evidence, the study identifies context specific sustainability pathways and policy responses that may also be relevant for other emerging markets. Finally, by linking its policy implications to the United Nations Sustainable Development Goals, particularly SDGs 7, 9, 13 and 16, the study offers evidence based guidance for policymakers seeking to meet international sustainability commitments, an issue that remains insufficiently addressed in the existing literature.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 presents the methodology, analytical techniques and data sources together with the measurement of variables. Section 4 reports and discusses the empirical findings. Section 5 concludes the study. Section 6 outlines the policy implications and Section 7 presents the limitations of the study and directions for future research.

2. Literature review

2.1. Theoretical overview

The study is grounded in theoretical perspectives that explain how institutional, economic and policy related factors interact in shaping environmental outcomes, with particular attention to the ecological footprint (EFP) in BRICS countries. Unlike conventional indicators that focus only on CO_2 emissions, the EFP captures the impact of human activity on a wider range of natural resources, including carbon absorption capacity, cropland, grazing land, forest products, fishing grounds and built up land [25]. Since it reflects both the environmental consequences of production and consumption patterns, the EFP provides a more comprehensive measure of ecological pressure [26].

Economic growth is closely connected to the broader debate on sustainable development. According to the Environmental Kuznets Curve (EKC) hypothesis, environmental degradation increases during the early stages of economic expansion but begins to decline once a certain level of development has been reached [27]. However, this relationship is not universal. In developing and resource dependent economies, economic growth may continue to intensify environmental degradation when effective regulatory frameworks are absent or weak [28].

Environmental policy stringency (EPS) is expected to affect environmental quality by encouraging firms to internalize the negative externalities generated by their activities through penalties, standards and regulatory constraints. Porter argues that well designed environmental regulations can stimulate innovation and produce gains in both productivity and environmental performance [29]. In this sense, EPS can encourage the adoption of green energy and environmentally friendly technologies by reshaping the incentives and constraints associated with regulatory compliance [8].

At the same time, progress in environmental patents and clean energy technologies represents an important link between economic growth and sustainability. Endogenous growth theory suggests that innovation supported by research and development, subsidies and international trade can help decouple economic activity from ecological degradation [30]. The effective development and transfer of green technologies can therefore improve resource efficiency, support sustainable production and reduce environmental harm [31].

Globalization and democratic institutions also jointly influence environmental outcomes in emerging economies through several interconnected channels that directly affect the EFP. Globalization shapes the ecological footprint through three main mechanisms. The first is the scale effect, which expands economic activity and consumption. The second is the composition effect, which reallocates production toward more or less pollution intensive sectors. The third is the technique effect, which supports technology diffusion and efficiency improvements [32, 33].

On the positive side, trade openness and capital flows can accelerate the diffusion of clean technologies, efficient production methods and renewable energy solutions. These processes may improve resource efficiency and reduce the land, water and carbon dimensions of the ecological footprint [32]. On the negative side, globalization may generate a pollution haven effect by attracting resource intensive industries to countries with weaker environmental regulations, thereby increasing ecological pressure and demand for biocapacity [33].

The overall direction and magnitude of these effects depend strongly on the quality of regulatory frameworks and institutional strength. Democratic institutions can act as an important moderating force through transparency, civil society participation, electoral accountability and access to environmental information [34]. In more mature democracies, stronger public awareness of ecological issues can lead to greater citizen demand for environmental protection. This, in turn, can pressure governments to adopt and enforce stricter environmental policies that offset the negative scale and composition effects of globalization [34]. This process may also stimulate eco innovation and reduce the likelihood of regulatory arbitrage.

By contrast, in weaker or transitional democracies, short term electoral incentives may encourage policymakers to prioritize rapid economic growth over long term sustainability. This can weaken policy enforcement and intensify the adverse environmental effects of globalization on the ecological footprint [35].

2.2. Hypothesis development

2.2.1. Nexus between EFP and economic growth

The relationship between economic growth, measured by GDP and the ecological footprint (EFP) has received substantial empirical attention. Nevertheless, the existing literature remains inconclusive, mainly because of methodological differences and context specific factors. Using the AMG estimator for 11 newly industrialized countries over the period 1977 to 2013, Destek and Sarkodie [36] identified an inverted U shaped relationship between GDP and EFP. Zambrano et al. [37], in a study covering 158 countries and Ansari et al. [38], in an analysis of leading renewable energy economies, found that GDP increases the ecological footprint. Similarly, Alola et al. [39], using the PMG ARDL approach for 16 EU countries, showed that a 1% increase in real GDP raises the ecological footprint by 0.81% in the long run. Kongbuamai et al. [40] also reported a positive relationship between GDP, green energy consumption, industrial activity and EFP in BRICS countries.

In contrast, other studies suggest that economic growth may contribute to better environmental outcomes. Applying the ARDL model to Finland for the period 1990 to 2021, Georgescu and Kinnunen [41] found that GDP per capita has a negative long run effect on environmental degradation, indicating an improvement in environmental quality. Similarly, Cosma et al. [42], using FMOLS and DOLS techniques for panel data covering 2000 to 2016, concluded that GDP helps reduce the ecological footprint and emphasized the potential role of economic growth in improving environmental performance.

Despite these contributions, several limitations remain. First, most previous studies rely heavily on mean based estimators, which may obscure distributional heterogeneity and quantile specific effects. Second, many analyses are based on restricted geographical samples or outdated periods, limiting their relevance for understanding recent dynamics in BRICS economies. Third, much of the literature still uses CO_2 emissions rather than broader and more comprehensive indicators such as the ecological footprint. These limitations reveal a clear research gap, namely the lack of robust quantile based evidence explaining how the GDP EFP relationship differs across various levels of ecological pressure in BRICS countries using recent data and a multidimensional environmental framework.

Accordingly, the following hypothesis is proposed:

H1: Economic growth has a significant positive effect on the ecological footprint in BRICS countries.

2.2.2. Nexus between EFP and globalization

The relationship between globalization (GLO) and the EFP remains unresolved in the empirical literature, as previous studies have reported positive, negative and statistically insignificant effects. Using FMOLS and DOLS estimators, Balsalobre Lorente et al. [43] examined developing countries in Eastern Europe and found that globalization improves environmental quality in economies with lower pollution levels. Similarly, Ibrahiem and Hanafy [44], in their study of Egypt for the period 1995 to 2009, reported that globalization reduces the ecological footprint. Salahuddin et al. [45], applying panel estimation techniques to 44 sub Saharan African countries, found that globalization has only a limited effect on environmental quality. Saud et al. [46], using data from 49 countries over the period 1990 to 2014, also showed that higher levels of globalization generally improve environmental outcomes, measured through carbon footprint, CO_2 emissions and ecological footprint.

In contrast, other studies indicate that globalization may increase environmental degradation. Destek et al. [47], analyzing Central and Eastern European countries from 1995 to 2015, found that higher levels of overall, economic and social globalization are associated with poorer environmental quality. Similarly, Alvarado et al. [48], in a study of 95 countries covering the period 1990 to 2018, reported a negative relationship between globalization and environmental sustainability, suggesting that globalization increases ecological pressure. Ahmed [13] further shows that political globalization consistently supports sustainable development in G7 economies, whereas social globalization has a negative and increasingly adverse effect across the distribution. Evidence from the United States also suggests that globalization has an asymmetric long run effect on environmental sustainability, with positive outcomes appearing only after globalization exceeds certain threshold levels [14].

Taken together, these findings suggest that the globalization EFP relationship is highly context dependent and may vary according to country characteristics, institutional quality and the level of environmental pressure. However, important limitations remain in the existing literature. In particular, there is still a lack of BRICS focused quantile regression studies that examine globalization together with eco innovation, environmental policy stringency and democratic institutions using recent data and a comprehensive ecological footprint indicator. This gap is especially relevant given the structural heterogeneity and increasing global importance of BRICS economies.

Based on the above discussion, the following hypothesis is proposed:

H2: Globalization has a significant positive effect on the ecological footprint in BRICS countries.

2.2.3. Nexus between EFP and environmental technology (ERT)

Environmental related technologies (ERTs) are introduced into production and processing activities to reduce environmental degradation. A growing body of research suggests that technological advancement can ease ecological pressure by lowering the environmental costs of economic activity. For instance, Sharif et al. [49], using the MM QR approach, examined the effects of green technological progress and clean energy on environmental quality and found that environmental technology (ET) reduces the EFP. Similarly, Sadiq et al. [50] identified an inverse relationship between environmental technology and EFP in the ten countries with the highest ecological footprints during the period 1990 to 2017. Comparable findings were reported by Hussain and Dogan [51] and Ahmad et al. [4], who found a negative association between ET and EFP in OECD countries, BRICS economies and 22 emerging countries respectively.

Additional evidence also supports the environmentally beneficial role of innovation. Kirikkaleli et al. [52], using time series analysis for the United States, found that patents in environmental technologies reduce the ecological footprint in the long run. Raihan [53] reported similar findings for China over the period 1985 to 2020. These results indicate that technological innovation, particularly in environmentally oriented areas, can improve resource efficiency, support cleaner production processes and contribute to stronger environmental sustainability.

However, the literature also offers contrasting evidence. Some studies argue that technological development may worsen environmental quality when investment in research and development is inadequate or when technological progress fails to achieve defined environmental objectives. For example, Chien et al. [54], in a study incorporating environmental taxation, green energy and environmental technology, found a significant positive relationship between these factors and the ecological footprint in Asian countries. This suggests that the environmental effect of technology depends not only on the existence of technological progress but also on the structure, quality and implementation of innovation.

Based on the above discussion, the following hypothesis is proposed:

H3: Environmental technology has a significant negative effect on the ecological footprint in BRICS countries.

2.2.4. Nexus between EFP and environmental policy stringency

With increasing awareness of environmental challenges, governments have introduced stricter regulations and targeted mitigation measures to support sustainable economic development. Several empirical studies suggest that EPS can play an important role in reducing ecological pressure. Using quantile regression, Afshan et al. [55] found that EPS reduces the EFP in OECD countries. Similarly, Ahmed [56], based on data from 20 OECD economies, reported that EPS promotes green innovation and lowers the ecological footprint. Yirong [57] identified a negative relationship between EPS and EFP in highly polluted economies, while Wang and Zhang [58] reported similar evidence for China. More generally, EPS has been shown to make a positive contribution to environmental sustainability [59].

Evidence from BRICS and other developing economies also supports this view. Ouni and Ben Abdallah [60] found that stronger environmental policy stringency helps reduce the ecological footprint in BRICS countries. In the same direction, Appiah et al. [61], using the CS ARDL approach, showed that EPS contributes to a decline in EFP. Rahman et al. [62] further demonstrated that, in Bangladesh, EPS can help reconcile economic growth with ecological sustainability by reducing pollution.

However, the empirical evidence is not fully consistent. Nathaniel et al. [63], examining the links among international trade, economic growth and EPS in the N 11 countries over the period 1990 to 2016, found that environmental policy stringency has only limited effectiveness in reducing the ecological footprint. This suggests that the environmental impact of EPS may depend on country specific institutional capacity, enforcement quality and broader structural conditions.

Based on the above discussion, the following hypothesis is proposed:

H4: Greater environmental policy stringency leads to a reduction in the ecological footprint in BRICS countries.

2.2.5. Nexus between EFP and democracy

A growing body of research has investigated the relationship between democracy and environmental quality, yet the empirical evidence remains inconclusive. Dai et al. [64], examining six ASEAN countries over the period 1995 to 2018, found that democracy reduces the ecological footprint and also plays a moderating role in shaping environmental outcomes. In contrast, Hasan et al. [65], using the PMG ARDL model for BRICS countries, reported that democracy is negatively related to environmental quality. Similarly, Ahmed et al. [16], applying second generation econometric techniques to G7 countries for the period 1985 to 2017, found evidence of an adverse association between democratic governance and environmental quality.

Other studies further confirm the ambiguous nature of this relationship. Li and Reuveny [34] reported a negative link between democratic governance and environmental sustainability. Akalin and Erdogan [66] also found that democracy worsens environmental quality by increasing the ecological footprint, although green energy contributes to improved ecological conditions in OECD countries. Halkos and Paizanos [67] identified a positive relationship between democracy and EFP, while York et al. [68] showed that the relationship between democracy and the ecological footprint is unclear across a sample of 142 countries.

More recent studies suggest that the effect of democracy depends on the broader institutional and policy context. Ahmed et al. [16] argued that countries with stronger democratic accountability are more capable of transforming economic growth into environmentally sustainable outcomes. Similarly, Ahmed et al. [21] found that democracy has an important moderating role in Pakistan's ecological footprint, with stronger democratic institutions increasing the environmental benefits of clean energy adoption.

Despite these contributions, an important limitation remains in the literature. Democracy has not been sufficiently examined together with other key determinants such as environmental policy stringency, globalization and eco innovation. This gap points to the need for updated BRICS focused quantile regression analysis that considers democracy alongside a broader set of institutional, economic and technological drivers using the ecological footprint as a comprehensive measure of environmental pressure.

Based on the above discussion, the following hypothesis is proposed:

H5: Democracy has a significant relationship with the ecological footprint, although the direction of the effect may vary.

Fig. 1 illustrates the development of the study's hypotheses.

2.3. Gaps in the existing literature

Previous studies have mostly examined relatively narrow dimensions of environmental degradation, often focusing on economic growth or globalization and frequently relying on traditional econometric techniques or single country analyses. In contrast, this study addresses a broader and more policy relevant research problem by jointly analyzing the effects of GDP, globalization, environmental technology, environmental policy stringency and democracy in BRICS countries. This perspective remains insufficiently developed in the existing literature.

By applying the MM QR approach, the study moves beyond conventional mean based estimation methods and identifies how these relationships differ across various levels of environmental degradation. In this way, it provides new evidence on the interaction between institutional conditions, economic transformation and environmental outcomes in rapidly developing economies.

The specific contribution of this study lies in its simultaneous assessment of environmental policy implementation and the role of democracy in developing country contexts, where policy enforcement is often uneven. This dimension has received limited attention in previous BRICS focused research.

3. Methodology

3.1. Data and variables

This study uses a balanced panel dataset for the five BRICS countries, namely Brazil, Russia, India, China and South Africa, covering the period from 1996 to 2022. The selected period is determined by data consistency and completeness. Specifically, 1996 is the earliest year for which fully balanced data are available for all BRICS economies across the OECD Environmental Policy Stringency Index, the KOF Globalization Index, ecological footprint, environmental technology and democracy indicators. Earlier starting years, such as 1990, would create data gaps, particularly for Russia and South Africa. The endpoint of 2022 enables the analysis to include the most recent available data, while also capturing the post 2008 recovery period, the implications of the 2015 Paris Agreement, intensified globalization dynamics and the effects of the COVID 19 period. With 27 years and 135 observations, the dataset provides adequate temporal coverage for robust panel econometric analysis while preserving a fully balanced structure.

In this study, ecological footprint is used as the dependent variable, while economic growth, globalization, environmental technology, environmental policy stringency and democracy are included as independent variables. The ecological footprint measures the environmental pressure generated by individuals or societies through resource

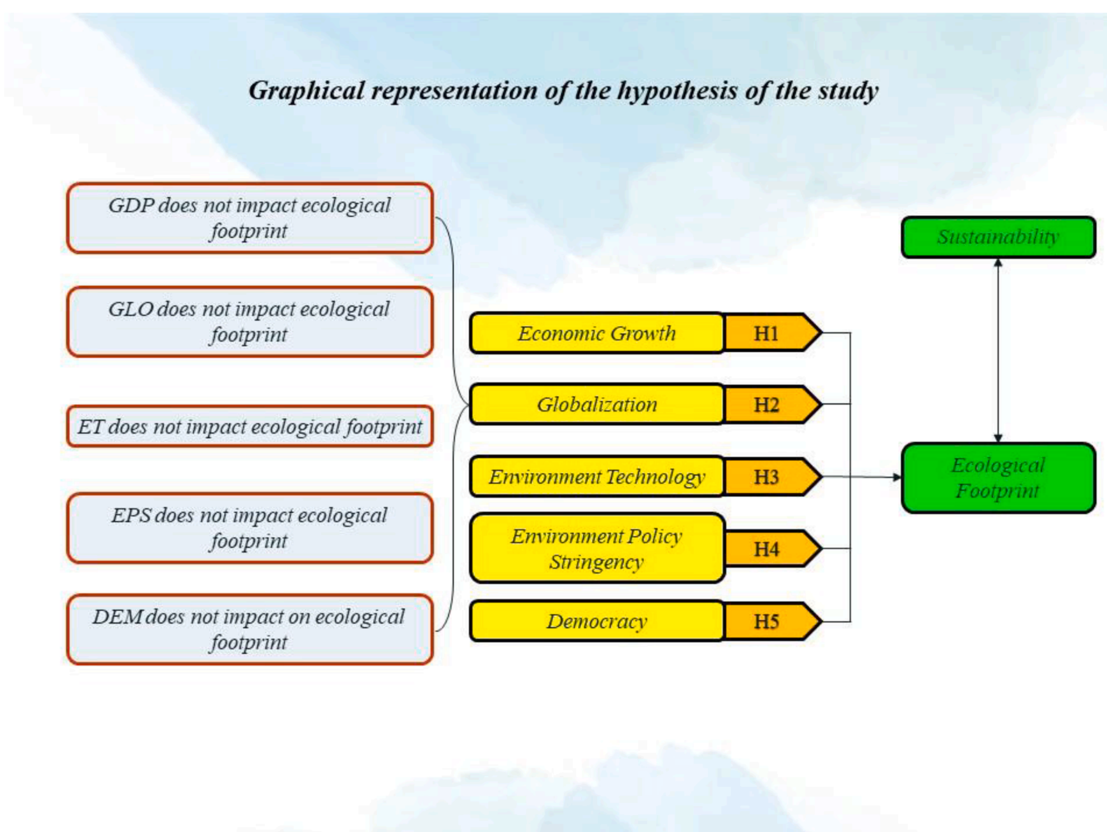

Fig. 1. Hypothesis development of the study.
Source: Author compilation.

consumption and waste production. It reflects the rate at which natural resources are consumed and waste is generated relative to ecological capacity. A higher ecological footprint therefore indicates more intensive use of natural resources and greater environmental pressure [37].

Economic growth refers to the increase in an economy's capacity to produce goods and services over time and remains one of the main macroeconomic objectives of national development. In this study, GDP is used as a proxy for economic growth. Globalization refers to the increasing interconnectedness of economies, societies and populations through the cross border movement of goods, services, capital, people and information. The KOF Globalization Index is used to measure globalization.

Environmental technology is defined as the share of environment related inventions in total domestic inventions across all technological fields. Environmental policy stringency (EPS) is a nationally and internationally comparable indicator that measures the strictness of environmental regulations. More precisely, it captures the extent to which environmental policies impose explicit or implicit costs on environmentally harmful behavior. The EPS index measures the stringency of 13 environmental policy instruments, with particular emphasis on climate and pollution related measures [69].

The democracy index is used to assess the quality of institutional governance through dimensions such as transparency, impartiality, independence, predictability and equality before the law. It includes indicators related to judicial independence, compliance with court decisions, corruption in the public sector and access to justice. Democracy may contribute to environmental sustainability by improving transparency, encouraging public participation and strengthening government accountability, thereby supporting the adoption and enforcement of environmentally responsible policies.

Table 1 presents the variables used in the study, together with their descriptions and data sources.

3.2. Model construction

This study investigates the effects of economic growth, globalization, environmental technology, environmental policy stringency and democracy on the ecological footprint. To conduct the empirical analysis, the study adopts a model based on the previous works of Rehman et al. [12] and Wang and Dong [70]. Accordingly, the baseline empirical function for this study is specified in Eq. (1).

$$\mathrm{EFP}_{\mathrm{it}} = \int \left(\mathrm{GDP}_{\mathrm{it}},\ \mathrm{GLO}_{\mathrm{it}}, \mathrm{ET}_{\mathrm{it}},\ \mathrm{EPS}_{\mathrm{it}},\ \mathrm{DEM}_{\mathrm{it}}\right) \tag{1}$$

Where t refers to time, and i refers to the number of nations. The economic model for this study is represented by Eq. (2).

Table 1
Descriptions of variables.

Name of Variables	Synoptic Terms	Descriptions & Measure	Sources of Data
Ecological Footprint	EFP	Ecological Footprint per person (Gha)	Global Footprint Network[1]
Economic Growth	GDP	Gross Domestic Product (constant 2015 US$)	WDI[2]
Globalization	GLO	Globalization Index	KOF[3]
Environmental Technology	ET	Environment Related Patent (percent of total innovation)	OECD[4]
Environmental Policy Stringency	EPS	Environmental Policy Stringency Index	OECD
Democracy	DEM	Democracy	V-Dem index

[1] https://data.footprintnetwork.org.
[2] https://databank.worldbank.org/.
[3] https://kof.ethz.ch/en/.
[4] https://data-explorer.oecd.org/.

$$\mathrm{EFP}_{\mathrm{it}} = \alpha_0 + \alpha_1 \mathrm{GDP}_{\mathrm{it}} + \alpha_2 \mathrm{GLO}_{\mathrm{it}} + \alpha_3 \mathrm{ET}_{\mathrm{it}} + \alpha_4 \mathrm{EPS}_{\mathrm{it}} + \alpha_5\ \mathrm{DEM}_{\mathrm{it}} \tag{2}$$

The equation can be transformed into logarithmic form, as presented in Eq. (3). This transformation helps reduce heteroscedasticity and improves the stability of the estimated coefficients. Accordingly, the econometric model used in this study is further specified in logarithmic form in Eq. (3).

$$\mathrm{lnEFP}_{\mathrm{it}} = \alpha_0 + \alpha_1 \mathrm{LGDP}_{\mathrm{it}} + \alpha_2 \mathrm{LGLO}_{\mathrm{it}} + \alpha_3 \mathrm{LET}_{\mathrm{it}} + \alpha_4 \mathrm{LEPS}_{\mathrm{it}} + \alpha_5\ \mathrm{LDEM}_{\mathrm{it}} + \varepsilon_{\mathrm{it}} \tag{3}$$

In Eq. (3), EFP represents the ecological footprint, GLO denotes globalization, ET refers to environmental technology, EPS indicates environmental policy stringency and DEM represents democracy. In addition, α_0 is the intercept, while α_1, α_2, α_3, α_4 and α_5 denote the estimated coefficients of LGDP, LGLO, LET, LEPS and LDEM respectively.

3.3. Econometric framework

This study examines a balanced panel dataset covering the five BRICS countries over the 27 year period from 1996 to 2022. Since the time dimension is larger than the cross sectional dimension (T > N), the use of a panel quantile regression framework is appropriate. In the first stage, several preliminary diagnostic tests are performed. These include the Jarque Bera test to assess the distributional properties of the data, tests for cross sectional dependence and slope heterogeneity and both first and second generation panel unit root tests. In addition, the Kao [71] and Pedroni [72] cointegration tests are applied to determine whether long run relationships exist among the variables. Slope homogeneity is also tested to account for possible country specific heterogeneity within the panel.

The main estimation method used in this study is the Method of Moments Quantile Regression developed by Machado and Santos Silva [73]. This technique is particularly suitable because it accounts for endogeneity, individual specific location effects and time effects simultaneously. These issues are not fully addressed by Powell's quantile regression [74] or by the conventional quantile regression approach of Koenker and Bassett [75]. To determine whether the estimated effects differ significantly across quantiles, the Wald test is employed. For robustness checks, the study also applies the Fully Modified Ordinary Least Squares and Dynamic Ordinary Least Squares estimators. Finally, the Dumitrescu Hurlin causality test [76] is used to identify the direction of causal relationships and to provide additional evidence for targeted policy formulation. The overall methodological framework of the study is presented in Fig. 2.

3.3.1. Cross-sectional dependence test

Addressing cross sectional dependence (CSD) in panel data is essential, particularly for BRICS economies, which are strongly interconnected through trade relations, financial flows and exposure to common global shocks such as oil price volatility, financial crises and climate related events. If cross sectional dependence is ignored, the analysis may produce biased standard errors, inefficient parameter estimates and unreliable statistical inference in subsequent procedures, including unit root, cointegration and regression tests [27].

For this reason, this study applies the Pesaran [77] CSD test to examine the presence of weak cross sectional dependence among the panel units. This test is appropriate and robust regardless of whether the time dimension (T) exceeds the cross sectional dimension (N), or whether the cross sectional dimension is larger than the time dimension. The statistical specification of the test is presented in the following equation.

$$CSD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \sqrt{\mathrm{T}_{\mathrm{ij}}}\ \hat{\rho}_{\mathrm{ij}} \right) \tag{4}$$

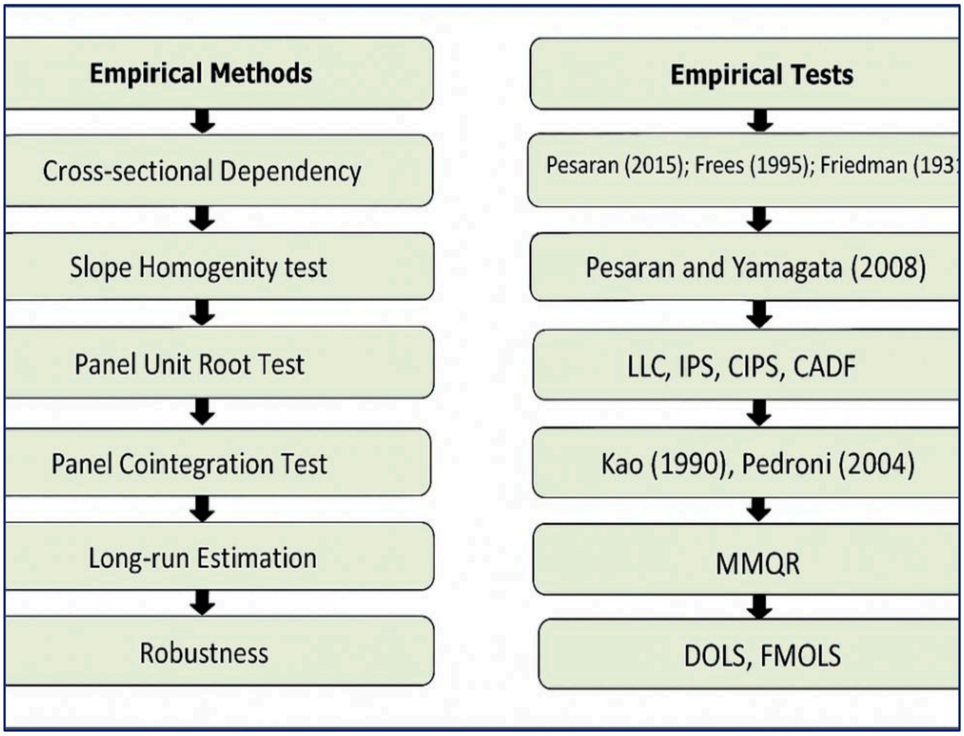

Fig. 2. Methodological Framework.
Source: Author compilation.

In this regard, N represents the sample, the letter T represents a period, and the letter $\hat{\rho}_{ij}$ represents the sample correlation between the residuals of countries i and j being estimated.

3.3.2. *Panel unit root test*

This study applies both first and second generation panel unit root tests to examine the stationarity properties and order of integration of the variables. As first generation tests, the Levin Lin Chu (LLC) test [78] and the Im Pesaran Shin (IPS) test [79] are employed. These tests assume cross sectional independence and slope homogeneity and provide an initial evaluation of whether the series contain a unit root. This step helps determine the appropriate order of differencing for the subsequent cointegration and regression analyses.

However, first generation tests may produce unreliable results when cross sectional dependence and slope heterogeneity are present, which is often the case among highly interconnected BRICS economies. Therefore, this study also applies the second generation Cross Sectionally Augmented IPS (CIPS) and Cross Sectionally Augmented Dickey Fuller (CADF) tests developed by Pesaran [80]. These tests extend the conventional ADF framework by including cross sectional averages of lagged levels and first differences, allowing them to control explicitly for cross sectional dependence and heterogeneous slope coefficients across panel units.

The main advantage of the CIPS and CADF tests is that they provide more robust and consistent results in the presence of strong cross sectional dependence and parameter heterogeneity. This reduces the risk of size distortions and misleading conclusions regarding non stationarity, which often affect first generation methods in globalized panel settings. Taken together, the combined use of first and second generation unit root tests ensures more reliable stationarity diagnostics before proceeding to cointegration and quantile regression analysis.

The equation underlying the IPS first-generation panel unit root test is as follows:

$$\Delta Y_{i,t} = \alpha_i + \beta_{i,t} + \gamma y_{i,t-1} + \sum_{j=1}^{k} \theta_k \Delta y_{i,t-j} + \varepsilon_{i,t} \tag{5}$$

Eq. (6) provides a mathematical expression for the CIPS test:

$$\mathrm{CIPS} = N^{-1} \sum_{i=1}^{N} t_i(N,T) \tag{6}$$

Where, $t_i(N,T)$ refers to the cross-section CADF statistic for the ith intersection. The CADF(p) regression for panel unit root testing is:

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + c_{1i}\bar{y}_{t-1} + c_{2i}\Delta \bar{y}_{t} + \sum_{j=1}^{p_i} \gamma_{ij}\Delta y_{i,t-j} + \varepsilon_{it} \tag{7}$$

Where y_{it}= variable for cross-section i at time t, $\Delta y_{it} = y_{it} - y_{i,t-1}$, $\bar{y}_t = \frac{1}{N}\sum_{i=1}^{N} y_{it}$(cross-sectional average), $\Delta \bar{y}_t = \bar{y}_t - \bar{y}_{t-1}$, p_i= lag length, and ε_{it}= error term.

3.3.3. *Panel cointegration test*

To examine whether a long run equilibrium relationship exists among the variables, this study applies panel cointegration tests. Specifically, the Kao [71] and Pedroni [72] cointegration tests are used to determine whether the variables move together over time despite being individually non stationary. These tests are widely used in panel data analysis to identify the presence of cointegration among relevant variables and to justify the application of long run estimation techniques. In particular, the Kao [71] test adopts a residual based approach for testing cointegration within a panel framework.

$$Z_{it} = \alpha_i + Z_{it-1} + \gamma Y_{it} + \epsilon_{it} \tag{8}$$

Next, we may use the residuals as the foundation for the Kao cointegration test.

$$\hat{\epsilon}_{it} = \sigma\hat{\epsilon}_{it-1} + \mu_{it} \tag{9}$$

When the test statistics are significant at the 10% level or below, the null hypothesis of no cointegration is rejected, confirming the existence of a long run relationship among the variables. Pedroni [72] offers an alternative panel cointegration framework that is particularly useful because it explicitly accounts for heterogeneity across panel units. A major advantage of this approach is that it allows cross sectional units to differ from one another while also accommodating multiple regressors within the cointegrating relationship.

$$\widehat{\Delta}Z_{it} = \alpha_i + \delta_t + \sum_{k=1}^{k} \gamma_{mi} Y_{mi,t} + \vartheta_{it} \tag{10}$$

Regarding the residual, we can write

$$\widehat{\vartheta}_{it} = \partial_i \widehat{\vartheta}_{it-1} + \mu_{it} \tag{11}$$

The error word is denoted by μ_{it}. It is possible to reject the null hypothesis for each equation, which states that there is no cointegration if the probability values are significant.

3.3.4. Slope homogeneity test

To formally evaluate whether slope homogeneity is present, this study applies the Pesaran and Yamagata [81] slope homogeneity test. This test provides a robust statistical assessment of whether the long run coefficients are the same across the five BRICS countries or differ from one country to another. Evidence of heterogeneous slopes would justify the use of heterogeneous panel estimators, such as MM QR, instead of more restrictive pooled or mean group approaches. In this way, the test improves the reliability and interpretability of the empirical results. Eq. (12) presents the specification of the slope homogeneity test.

$$\Delta = \sqrt{N\left(\frac{N^{-1}S\% - K}{\sqrt{2K}}\right)} \text{ and } \Delta_{adj} = \sqrt{N\left(\frac{N^{-1}S\% - K}{\sqrt{\frac{2K(t-k-1)}{T+1}}}\right)} \tag{12}$$

3.3.5. Quantile regression model

This study uses the Method of Moments Quantile Regression (MM-QR), developed by Machado and Santos Silva [73], as the main estimation method. The key advantage of MM-QR is its capacity to address several important econometric issues at the same time, including endogeneity through the method of moments framework, unobserved individual specific location effects and time specific effects. These characteristics make the method especially appropriate for panel data analysis in complex and heterogeneous empirical settings. In contrast, Powell's quantile regression [74] and the conventional quantile regression model of Koenker and Bassett [75] do not fully account for these issues, which may lead to biased or incomplete estimates, particularly in panel data applications.

A further strength of MM-QR is that it estimates the full conditional distribution of the ecological footprint rather than focusing only on the conditional mean [82]. This allows the study to examine whether the marginal effects of institutional, economic and technological factors differ across low, medium and high levels of environmental pressure. Such distributional analysis is particularly relevant for BRICS countries, where ecological conditions and policy responses vary considerably, making mean based estimates potentially misleading. By combining robustness to endogeneity with a distribution sensitive framework, MM-QR provides more reliable and policy relevant results than traditional mean based models or standard quantile regression techniques.

$$\begin{aligned} Q_{LEFP_{it}}\left(\tau|X_{it,\ \mu_i}\right) = {} & \mu_i + \delta_{1\tau}LGDP_{it} + \delta_{2\tau}LGLO_{it} + \delta_{3\tau}LET_{it} + \delta_{4\tau}LDEM_{it} \\ & + \ + \ \delta_{5\tau}LEPS_{it} + \delta_{5\tau}X_{it} + \ \in_{it} \end{aligned} \tag{13}$$

Here, the quantile measure, the quantile fraction, and the explanatory variables are denoted by τ, $Q_{lnEFP_{it}}\ (\tau X_{it})$ and X_{it} respectively.

3.3.6. Robustness checking

This study applies FMOLS [83] and DOLS [84] as additional robustness checks to confirm the long run relationships estimated through the MM QR model. Both estimators are designed for cointegrated panel data and offer important advantages compared with conventional OLS. FMOLS corrects for endogeneity using non parametric adjustments and addresses serial correlation through parametric corrections, thereby providing consistent and unbiased estimates of long run elasticities even when the explanatory variables are correlated with the error term. DOLS follows a parametric approach by including leads and lags of the first differenced regressors, which helps remove contemporaneous correlation between the regressors and the disturbance term.

Taken together, FMOLS and DOLS provide efficient and super consistent estimates of the long run effects of globalization, environmental policy stringency, environmental technology, democracy and GDP on the ecological footprint. Their results serve as a useful benchmark for comparison with the MM-QR estimates and help verify that the quantile specific findings are not driven by model dependent estimation bias. Therefore, the use of FMOLS and DOLS strengthens the robustness of the empirical analysis in the presence of cointegration, endogeneity and cross country heterogeneity among BRICS economies.

3.3.7. Wald test

This study also employs the Wald test to examine whether the estimated coefficients of the explanatory variables vary significantly across different quantiles of the ecological footprint distribution. Within the MM-QR framework, the Wald test is particularly useful because it provides a formal joint assessment of coefficient equality, or asymmetry, across quantiles. This allows the study to determine whether the marginal effects of globalization, environmental policy stringency, environmental technology, democracy and GDP remain stable or differ across low, medium and high levels of environmental pressure.

Unlike informal graphical comparisons or conventional mean based methods, the Wald test provides objective statistical evidence on the existence of quantile specific heterogeneity. It therefore strengthens both the reliability and the policy relevance of the distributional findings. The test is specified in the following equation:

$$\begin{aligned} LEFP_{it} = {} & \alpha_0 + \alpha_1\left(LGDP_{it} - LGDP^*_{it}\right) + \alpha_2\left(LDEN_{it} - LDEM^*_{it}\right) \\ & + \alpha_3\left(LEPS_{it} - LEPS^*_{it}\right) + \alpha_4\left(LGLO_{it} - LGLO^*_{it}\right) \\ & + \alpha_5\left(LET_{it} - LET^*_{it}\right) + \ \mu_{it} \end{aligned} \tag{14}$$

3.3.8. Causality test

Granger [85] originally introduced the causality test to identify the direction of relationships among variables. However, the conventional Granger causality framework has several limitations, particularly in panel data settings characterized by cross sectional dependence, where its underlying assumptions may be violated and the results may become unreliable. To overcome this limitation, this study applies the more advanced Dumitrescu and Hurlin panel causality test developed by Dumitrescu and Hurlin [76].

This method extends the traditional Granger non causality approach to heterogeneous panel data by estimating a Wald statistic for each cross sectional unit and then averaging these statistics to obtain the overall panel test statistic. It is therefore more suitable for panel datasets such as those of the BRICS countries, where cross country interdependence and heterogeneity are important characteristics. The Dumitrescu and Hurlin panel causality model is expressed as follows:

$$y_{it} = \alpha_i + \sum_{j-1}^{j} \lambda_i^j y_{i(t-j)} + \sum_{j-1}^{j} \beta_i^j x_{i(t-j)} + \varepsilon_{it} \tag{15}$$

In this context, x and y signify the observables.

4. Results and discussion

4.1. Summary statistics, CSD, and SH test

The summary statistics presented in Table 2 indicate that all variables comprise 135 observations. Among the variables, LGDP has the highest mean value, at 27.86, while LEPS records the lowest minimum value, at −0.362. With respect to dispersion, LGDP exhibits the greatest standard deviation, suggesting substantial variability across the sample, whereas DEM shows the lowest standard deviation, indicating relatively limited variation over the observed period.

In terms of distributional characteristics, LEFP, LGLO, and LEPS are negatively skewed, while LGDP and DEM display positive skewness. The Jarque-Bera test results further indicate that the variables deviate from normality. This evidence of non-normal distribution provides methodological support for the application of quantile regression, as this approach is less dependent on strict distributional assumptions and is therefore appropriate for the present empirical analysis.

Table 3 presents the correlation matrix for the study variables. The results indicate that LEFP is positively and statistically significantly correlated with both LGLO and LEPS at the 1% level, suggesting that higher levels of globalization and greater environmental policy stringency are associated with increased environmental pressure. Conversely, LEFP is negatively and significantly correlated with LET and LDEM, indicating that improvements in environmental technology and stronger democratic institutions are associated with lower environmental pressure.

LGDP is positively correlated with LET, implying that economic growth may be linked to greater development of environmental technologies. At the same time, LGDP exhibits a strong negative correlation with LDEM, suggesting an inverse association between economic growth and democratic institutions within the sample. In addition, the negative and significant correlation between LDEM and LEFP further supports the view that democratic institutions may contribute to mitigating environmental degradation.

Overall, the correlation results reveal several relevant associations among the variables and provide preliminary insight into the potential determinants of environmental pressure in BRICS countries. However, these pairwise relationships should be interpreted with caution, as correlation does not imply causality.

Table 4 presents the results of the cross-sectional dependence test for the study variables. The findings indicate that all variables, namely LEFP, LGDP, LGLO, LEPS, LET, and LDEM, are statistically significant at the 1% level, with p-values of 0.000 or below 0.01. This high level of statistical significance confirms the presence of cross-sectional dependence in the panel.

The presence of cross-sectional dependence implies that shocks or changes occurring in one country may spill over to other countries in the sample. This pattern is particularly plausible in the context of BRICS economies, which are economically, institutionally, and globally interconnected. Therefore, the results justify the use of econometric techniques that explicitly account for cross-sectional dependence, thereby ensuring more reliable and consistent empirical estimates.

Table 5 presents the results of the slope homogeneity test, which assesses whether the slope coefficients are homogeneous across cross-sectional units. The test statistics for Delta and adjusted Delta are 4.764 and 5.834, respectively, with p-values of 0.000, indicating statistical significance at the 1% level. These findings reject the null hypothesis of slope homogeneity and confirm the presence of slope heterogeneity within the panel. This implies that the relationships among the variables vary across BRICS countries.

The evidence of slope heterogeneity supports the application of econometric methods that allow coefficients to differ across panel units rather than imposing a common effect for all countries. In this context, quantile regression is particularly appropriate, as it can capture both country-specific and distribution-specific variations in the effects of the explanatory variables.

4.2. Panel unit root test

Following the confirmation of cross-sectional dependence and slope

Table 3
Result of the correlation test.

Variable	LEFP	LGDP	LGLO	LET	LEPS	LDEM
LEFP	1.000					
LGDP	−0.095	1.000				
	(0.2977)					
LGLO	0.6448	0.0360	1.000			
	(0.0000)	(0.6962)				
LET	−0.2248	0.3844	0.3087	1.000		
	(0.0136)	(0.0000)	(0.0006)			
LEPS	0.3727	−0.1604	0.573	0.0854	1.000	
	(0.0000)	(0.0802)	(0.0000)	(0.3534)		
LDEM	−0.3425	−0.7814	−0.0877	0.0962	0.1268	1.000
	(0.0001)	(0.0000)	(0.3411)	(0.2958)	(0.1677)	

Note: P-value in parentheses.

Table 4
CSD Test result.

Variable	Test statistics	P- value
LEFP	5.74***	(0.000)
LGDP	15.08***	(0.000)
LGLO	15.08***	(0.000)
LEPS	9.6***	(0.000)
LET	3.02***	(0.003)
LDEM	4.56***	(0.000)

Note:.
*** $p < 0.01$.

Table 5
Result of the SH test.

	Test stat.	p-value
Delta	4.764***	(0.000)
Delta_{adj}	5.834***	(0.000)

Note:.
*** $p < 0.01$.

Table 2
Summary statistics.

Variable	N	Mean	Max	Min	Std. dev	Kurtosis	Skewness	JB
LEFP	135	0.9564	1.8522	−0.3073	0.6282	2.4822	−0.6889	10.95***
LGDP	135	27.867	30.290	26.0290	1.0309	2.8809	0.2626	1.45
LGLO	135	4.1054	4.2786	3.7247	0.2842	3.5488	−1.0223	22.41***
LEPS	135	−0.3628	1.0799	−2.8903	0.8398	2.9450	−0.3797	2.90
LET	135	2.2300	2.8243	1.1052	0.3159	4.2556	−1.0105	28.31***
LDEM	135	0.4491	0.8490	0.0790	0.2842	1.3914	0.2064	13.79***

Note:.
*** $p < 0.01$.

heterogeneity in the panel dataset, it is essential to examine the stationarity properties of the variables in order to avoid spurious regression results. Table 6 presents the results of the LLC and IPS panel unit root tests, which assess whether the study variables are stationary at their levels and first differences.

The findings indicate that most variables are non-stationary in their level form but become stationary after first differencing. Specifically, LEFP, LGDP, and LET are statistically significant at the 1% or 5% level in both the LLC and IPS tests after first differencing, confirming their stationarity. Similarly, LDEM and LEPS, which appear to be non-stationary at levels, become stationary after first differencing according to the IPS test, although LEPS remains statistically insignificant in the LLC test. In contrast, LGLO is stationary in level form in both tests, suggesting relatively more stable time-series properties.

Overall, the results indicate that most variables are integrated of order one, I(1), thereby supporting the use of econometric techniques suitable for non-stationary panel data, particularly panel cointegration methods and quantile regression analysis.

Table 7 presents the results of the CIPS and CADF unit root tests, which are employed to account for cross-sectional dependence in panel data, a common feature of multi-country studies such as those involving BRICS economies. By incorporating cross-sectional averages, these second-generation tests provide a more reliable assessment of stationarity and help overcome the limitations of conventional unit root tests in the presence of interdependence across panel units.

The results indicate that several variables are non-stationary in level form but become stationary after first differencing. For example, LEFP is non-stationary at levels in both the CIPS and CADF tests, but becomes statistically significant after first differencing, at the 1% level in the CIPS test and the 5% level in the CADF test. In contrast, LGDP, LGLO, LEPS, and LET appear stationary in level form in both tests, with LGLO and LET providing particularly strong evidence of stationarity at the 1% level. LDEM, however, remains non-stationary at levels and becomes stationary only after first differencing in both tests.

Overall, these findings suggest that the variables are integrated either of order zero, I(0), or order one, I(1), indicating a mixed order of integration. This supports the use of panel cointegration techniques and quantile regression methods that are suitable for variables with mixed integration properties and that account for cross-sectional dependence.

4.3. Panel cointegration test

Table 8 presents the results of the panel cointegration tests based on the Kao and Pedroni approaches, which are employed to examine the existence of a long-run equilibrium relationship among the study variables. The Kao test results show that all reported statistics, including the Modified Dickey-Fuller t-statistic, Dickey-Fuller t-statistic, ADF t-statistic, and their unadjusted counterparts, are statistically significant at the 1% or 5% levels. These findings provide strong evidence of cointegration among the variables, implying the existence of a stable long-run relationship despite potential short-run fluctuations.

The Pedroni test results further support this conclusion. Specifically, the Modified Phillips–Perron t-statistic and Phillips-Perron t-statistic are significant at the 5% and 1% levels, respectively, while the Augmented Dickey-Fuller t-statistic is significant at the 1% level. The consistency of the results across both the Kao and Pedroni tests confirms the existence of a long-run association among economic growth, globalization, environmental technology, environmental policy stringency, democracy and the ecological footprint in BRICS countries.

Overall, these findings justify the application of estimation techniques suitable for cointegrated panel data, including quantile regression models and other long-run panel estimators.

Table 6
Results of LLC and IPS test.

Variables	LLC At level	1st Diff.	IPS At level	First Diff.
LEFP	−1.5359*	−3.5723***	−1.3234	−3.2319***
LGDP	−1.6894**	−2.1594**	−1.1753	−2.8365***
LGLO	−5.2927***	−2.2158**	−3.1624***	−2.5912***
LEPS	0.7344	1.0154	−1.9326	−3.6254***
LET	−1.6809***	−5.7271***	−2.2407***	−3.6865***
LDEM	0.5214	−2.8070***	−0.695	−2.9045***

Note:.
*** $p < 0.01$.

Table 7
Results of CIPS and CADF tests.

Variables	CIPS At level	First Diff.	CADF At level	First Diff.
LEFP	−1.614	−4.801***	−1.451	−2.345**
LGDP	−2.600***	−2.984***	−2.645***	−2.498**
LGLO	−3.177***	−4.171***	−2.420**	−3.054***
LEPS	−2.892***	−5.140***	−1.891	−3.071***
LET	−3.131***	−5.371***	−3.176***	−3.983***
LDEM	−1.760	−4.010***	−1.966	−2.648***

Note:.
** $p < 0.05$, and.
*** $p < 0.01$.

Table 8
Cointegration result.

Kao Cointegration test		Pedroni Cointegration	
Estimator	Statistics	Estimator	Statistic
Modified Dickey-Fuller t	−2.3639***	Modified Phillips-Perron t	1.7623**
Dickey-Fuller t	−1.7853**	Phillips-Perron t	−7.9582***
ADF t	−1.702**	Augmented Dickey-Fuller t	−4.4423***
Unadjusted modified Dickey-Fuller t	−3.4877***		
Unadjusted Dickey-Fuller t	−2.0504***		

Note:.
** $p < 0.05$, and.
*** $p < 0.01$.

4.4. Quantile regression model

Table 9 reports the quantile regression results, while Fig. 3 illustrates the effects of the explanatory variables on the ecological footprint in BRICS countries. The findings reveal a positive and statistically significant relationship between GDP (LGDP) and the ecological footprint (LEFP) across all quantiles, indicating that economic growth is consistently associated with greater environmental pressure in BRICS economies. However, the magnitude of this effect declines from 0.519 in the lowest quantile (Q1) to 0.402 in the highest quantile (Q9), suggesting that the strength of the relationship weakens as environmental pressure increases. This pattern may imply that, in countries or periods already characterized by high ecological degradation, the marginal environmental cost of additional economic growth becomes relatively smaller, possibly due to partial mitigation measures, technological adaptation, or improvements in resource efficiency at more advanced stages of development. For BRICS countries, which are characterized by rapid industrialization and sustained economic expansion, this finding highlights the continuing challenge of reconciling growth objectives with environmental sustainability, particularly during the early and intermediate stages of development. Similar findings have been reported by Ahmed et al. [86], Uddin et al. [87], Fakher and Ahmed [88], and Destek and Sinha [47]. In contrast, Alruweili [89] found a negative long-run relationship between LGDP and LEFP, which differs from the present findings.

The results also indicate a strong, positive, and statistically

Table 9
Results of quantile regression.

Variable	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9
LGDP	.5190***	.508***	.490***	.471***	.455***	.440***	.427***	.418***	.402***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LGLO	.689***	.672***	.643***	.613***	.587***	.562***	.542***	.527***	.501***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LEPS	−0.041*	−0.040**	−0.0385*	−0.036***	−0.035***	−0.033***	−0.032***	−0.031***	−0.030***
	(0.055)	(0.034)	(0.011)	(0.002)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LET	−0.0338	−0.0335	−0.0332	−0.032*	−0.032***	−0.032*	−0.030***	−0.031***	−0.031
	(0.327)	(0.271)	(0.170)	(0.089)	(0.000)	(0.071)	(0.050)	(0.161)	(0.260)
LDEM	.4057**	.404***	.401***	.399***	.397***	.395***	.393***	.392***	.389***
	(0.014)	(0.005)	(0.000)	(0.0000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Note:.
* $p < 0.10$,.
** $p < 0.05$, and.
*** $p < 0.01$.

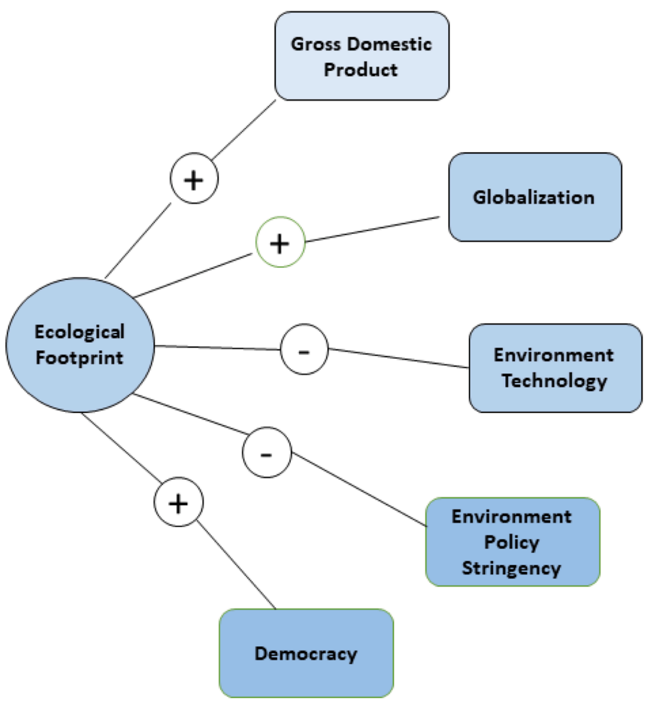

Fig. 3. Impact of Explanatory Factors on EFP.
Source: Author compilation.

significant relationship between globalization (LGLO) and LEFP across all quantiles in the BRICS sample. The estimated coefficients gradually decline from 0.689 in Q1 to 0.501 in Q9, suggesting that the environmental impact of globalization is more pronounced at lower levels of ecological degradation and somewhat weaker in more environmentally stressed contexts. This finding implies that as BRICS countries become more integrated into the global economy through trade, investment, and technology flows, their ecological footprint tends to increase. At the same time, the declining coefficient pattern across quantiles may reflect differences in the capacity of BRICS economies to absorb and manage the environmental consequences of globalization. In countries already experiencing greater ecological stress, mitigation mechanisms or structural adjustments may already be in place, thereby reducing the marginal environmental effect of further globalization.

In contrast, environmental policy stringency (LEPS) exhibits a negative and statistically significant relationship with LEFP across all quantiles, indicating that stricter environmental policies contribute to improvements in environmental quality in BRICS countries. More specifically, a 1% increase in environmental policy stringency reduces LEFP by 0.041% in the lowest quantile, while the effect decreases to 0.030% in the highest quantile. This pattern suggests that environmental policies may be more effective in contexts with relatively lower levels of environmental degradation, where implementation and enforcement constraints are less severe. In highly polluted contexts, the smaller marginal effect may reflect institutional weaknesses, limited enforcement capacity, or the greater difficulty of addressing deeply embedded environmental problems. For BRICS countries, where economic development has often progressed faster than environmental regulation, this finding underscores the importance not only of designing strong environmental policies but also of ensuring their effective and consistent implementation. This result is consistent with the findings of Dai and Du [90] and Sohag et al. [91].

The estimates also show a clear and consistent negative relationship between environmental technology (LET), proxied by environmental patents, and LEFP across all quantiles. The results indicate that advances in green technology improve environmental quality throughout the distribution, although the magnitude of the effect varies. In the first quantile, a unit increase in LET leads to a 0.033% reduction in LEFP, while the effect remains broadly similar in the middle quantile, at 0.032%. Notably, in the highest quantile, which represents the most environmentally stressed contexts, the reduction becomes substantially larger, reaching 0.31%. This stronger effect at higher quantiles suggests that environmental innovation becomes particularly effective where ecological pressure is greatest. For BRICS economies, which often face severe environmental challenges due to rapid industrialization, this finding highlights the importance of investing in and scaling up environmental technologies to achieve meaningful reductions in ecological degradation. Moreover, progress in environmental technology may reduce the costs of cleaner production methods and improve access to renewable and low-emission energy options, thereby generating broader environmental benefits. The negative association identified here is consistent with the findings of Hussain and Dogan [51], Kirikkaleli et al. [52], Ahmad et al. [4], and Yasmeen et al. [92]. However, not all studies report similar results. For example, Sayar [93], Dar et al. [94], and Bozatli and Akca [95] either found no significant relationship or reported that environmental technology did not improve environmental quality in certain country groups.

Finally, the quantile regression estimates reveal a consistently positive and statistically significant relationship between democracy (LDEM) and LEFP across all quantiles in BRICS countries. The coefficients range from 0.4057 in Q1 to 0.389 in Q9, suggesting that higher levels of democracy are associated with greater environmental pressure across the full distribution of ecological degradation. Although this finding may appear counterintuitive, it may reflect the specific institutional and developmental context of BRICS economies, where democratization can coincide with rapid industrialization, expanding consumption, and uneven enforcement of environmental regulations. In such settings, greater democratic openness may be accompanied by increased access to energy, transport, and consumer goods, thereby raising the ecological footprint if environmental governance and green infrastructure do not improve at a comparable pace. In some developing economies, governments may also prioritize short-term economic gains and visible infrastructure projects during electoral cycles, sometimes at the expense of environmental sustainability. The slight decline in the democracy coefficient from lower to higher quantiles indicates that this positive effect weakens somewhat as ecological pressure intensifies, possibly reflecting stronger public demand for environmental reforms or gradual institutional learning in more environmentally burdened contexts. Similar findings have been reported by Ahmed et al. [16] and Akalin and Erdogan [66]. Parks and Roberts [96], drawing on modernization theory, likewise support this interpretation. However, the present result differs from the conclusions of other studies, including Dai et al. [64].

4.5. Wald test

Table 10 presents the results of the Wald test, which is employed to determine whether the slope coefficients differ significantly across the quantiles estimated in the quantile regression model. Specifically, the test examines whether the effects of the explanatory variables, namely LGDP, LGLO, LEPS, LET, and LDEM, vary across Q0.20, Q0.40, Q0.60, and Q0.80.

The findings indicate that the Wald statistics for all variables are statistically significant at the 1% level, with p-values of 0.000. This provides strong evidence of heterogeneity in the effects of the explanatory variables on LEFP across the conditional distribution. In other words, the effects of economic growth, globalization, environmental policy stringency, environmental technology, and democracy on environmental degradation are not constant, but differ according to the level of environmental pressure.

In the context of BRICS countries, these results further justify the use of quantile regression techniques, as they are better suited to capturing distributional heterogeneity and producing more policy-relevant insights than conventional mean-based models.

4.6. Robustness test

The FMOLS and DOLS results reported in Table 11 largely confirm the findings of the MM-QR analysis presented in Table 9. Both estimators indicate a positive and statistically significant relationship between LGDP and LEFP. Specifically, the FMOLS results show that a 1% increase in LGDP is associated with a 0.54% increase in LEFP, while the DOLS estimates indicate a corresponding increase of 0.42%. Consistent with the quantile regression results, globalization also has a positive and statistically significant effect on LEFP at the 1% level.

The results further show that both environmental policy stringency (LEPS) and environmental technology (LET) contribute to environmental improvement by reducing the ecological footprint. According to the FMOLS estimates, a one-unit increase in LEPS and LET reduces LEFP by 0.11% and 0.311%, respectively. A similar pattern is observed in the DOLS results, further confirming the robustness of these findings.

With regard to democracy, however, the results are less consistent across estimators. While the DOLS estimates suggest a negative relationship between democracy and LEFP, the FMOLS results indicate a positive association. This mixed evidence implies that the environmental effect of democracy may be sensitive to model specification. Nevertheless, the positive coefficient obtained from the FMOLS estimator suggests that, under certain conditions, greater democratic development may be associated with a higher ecological footprint, possibly through increased consumption, broader access to resources, or intensified resource use.

Table 11
Result of DOLS & FMOLS.

Variables	FMOLS	DOLS
LGDP	.54139***	.4280***
	(0.000)	(0.000)
LGLO	.9604***	1.5418***
	(0.000)	(0.000)
LEPS	−0.1121***	−0.0045***
	(0.000)	(0.000)
LET	−0.3122***	−0.0544***
	(0.000)	(0.000)
LDEM	2.3116***	−1.934***
	(0.000)	(0.000)
Constant	13.23***	8.138***
	(0.000)	(0.000)
Observation	120	120
R^2	.7479	.929
Adjusted R^2	.7344	.921

Note:.
*** $p < 0.01$.

4.7. Dumitrescu-Hurlin causality test

Table 12 presents the results of the Dumitrescu-Hurlin panel causality test, which examines the direction of causality between the ecological footprint (LEFP) and the key explanatory variables across BRICS countries. The findings reveal a combination of unidirectional and bidirectional causal relationships, providing important insights into the dynamic interactions between environmental pressure and its determinants in these rapidly developing economies.

A unidirectional causal relationship is identified from LGDP to LEFP, indicating that changes in economic growth significantly affect the ecological footprint, while the reverse relationship is not supported. This finding highlights the role of economic expansion as an important driver of environmental degradation in BRICS countries. A similar unidirectional causal relationship is observed from LET to LEFP, suggesting that

Table 10
Result of the Wald test.

Variables	$Q_{.20}$	$Q_{.40}$	$Q_{.60}$	$Q_{.80}$
LGDP-LGDP	101.27***	223.86***	249.7***	154.83***
	(0.000)	(0.000)	(0.000)	(0.000)
LGLO-LGLO	1951.2***	3703.6***	3021.99***	1436.32***
	(0.000)	(0.000)	(0.000)	(0.000)
LEPS-LEPS	279.92***	626.07***	677.65***	400.65***
	(0.000)	(0.000)	(0.000)	(0.000)
LET- LET	642.55***	1593.02***	1828.65***	1113.67***
	(0.000)	(0.000)	(0.000)	(0.000)
LDEM- LDEM	124.15***	341.65***	467.29***	336.44***
	(0.000)	(0.000)	(0.000)	(0.000)

Note:.
*** $p < 0.01$.

Table 12
Dumitrescu-Hurlin causality test results.

Null Hypo.	Z-bar	Z-bar tide	Decision
LEFP≠LGDP	1.421	1.028	Unidirectional
LGDP≠LEFP	3.285***	2.585***	
LEFP≠LGLO	7.834***	6.325***	Bidirectional
LGLO≠LEFP	2.683***	2.035***	
LEFP≠LEPS	2.6915***	2.077***	Bidirectional
LEPS≠LEFP	13.012***	10.602***	
LEFP≠LET	1.285	0.9169	Unidirectional
LET≠LEFP	4.939***	3.934***	
LEFP≠LDEM	5.137***	4.097***	Bidirectional
LDEM≠EFP	3.921***	3.0934***	

Note:.
*** $p < 0.01$.

advances in green technology significantly influence environmental quality, whereas ecological pressure does not appear to stimulate technological progress in return. This underscores the importance of proactive investment in environmental innovation rather than relying on environmental deterioration itself to induce technological change.

By contrast, globalization (LGLO), environmental policy stringency (LEPS) and democracy (LDEM) exhibit bidirectional causality with LEFP. This implies the existence of feedback effects, whereby these variables not only shape environmental outcomes but are also influenced by the level of environmental pressure. For example, rising ecological degradation may prompt BRICS governments to strengthen environmental regulations or encourage greater public and institutional engagement in environmental governance. Similarly, globalization processes may evolve in response to environmental conditions and increasing sustainability pressures.

Overall, these results suggest that the relationship between the ecological footprint and its determinants in BRICS countries is dynamic and, in several cases, mutually reinforcing. This has important implications for policy design, particularly in terms of integrating economic growth, globalization, environmental regulation, technological innovation, and institutional development into long-term environmental management strategies.

5. Conclusion

This study examines the evolving relationships between the ecological footprint (EFP) and economic growth, globalization, environmental technology, environmental policy stringency and democracy in BRICS countries over the period 1996–2022. By applying advanced panel econometric techniques, including quantile regression, cointegration analysis and causality testing, the study provides robust evidence on the heterogeneous and dynamic interactions among these variables.

The findings confirm the existence of a long-run cointegrating relationship among the variables, as supported by both the Kao and Pedroni tests. The quantile regression results indicate that GDP, globalization and democracy exert positive and statistically significant effects on environmental degradation across all quantiles. However, the effects of GDP and globalization decline as ecological pressure intensifies, suggesting the possible presence of adaptive responses, structural adjustment, or policy moderation in more environmentally stressed contexts. In contrast, democracy maintains a relatively stable positive effect on environmental pressure, highlighting the complex relationship between democratic openness, consumption expansion, and institutional enforcement in developing economies.

Environmental policy stringency and environmental technology are found to reduce the ecological footprint, with stronger effects observed at higher quantiles, where environmental degradation is more severe. These findings underline the critical importance of institutional capacity and technological innovation in mitigating environmental damage, particularly in highly polluted settings.

The Dumitrescu-Hurlin causality results reveal bidirectional causal relationships between LEFP and globalization, environmental policy stringency, and democracy. This suggests that environmental degradation not only responds to institutional and economic factors but may also influence their future evolution. By contrast, GDP and environmental technology exhibit unidirectional causality toward LEFP, highlighting their important role in shaping environmental outcomes in BRICS countries.

6. Policy recommendations

The findings suggest that a comprehensive set of policy actions is required to align economic development with environmental sustainability in BRICS countries. First, governments should prioritize the decoupling of economic growth from environmental degradation. This can be achieved through the adoption of circular economy principles, which promote resource efficiency, the continuous use of recyclable materials, and waste minimization, thereby reducing dependence on natural resources. In addition, replacing or complementing conventional GDP indicators with green GDP measures would improve policymaking by incorporating the environmental costs of economic expansion into development planning.

Second, BRICS countries should strengthen support for environmental technology and green innovation. This may include tax incentives for firms that adopt clean energy, increased public investment in green research and development, and expanded access to affordable green finance for start-ups and small and medium-sized enterprises. Technology diffusion could also be accelerated through regional innovation hubs and stronger technological cooperation among BRICS countries.

Third, environmental policy stringency should be accompanied by effective implementation. Although stricter environmental regulations can improve environmental quality, their practical enforcement often remains insufficient. To strengthen regulatory credibility, governments should establish independent environmental monitoring bodies, expand the use of digital tools for environmental surveillance and impose meaningful penalties on violators. Mandatory environmental reporting and regular environmental audits for companies would further enhance transparency and accountability.

Fourth, policymakers should ensure that international trade arrangements are consistent with environmental objectives. This may involve introducing environmentally adjusted tariffs, expanding environmental labeling requirements for traded products, and improving disclosure standards related to emissions and environmental performance. In this way, BRICS countries can pursue trade-driven growth while limiting its ecological costs.

Fifth, democracy should be used as a mechanism for strengthening, rather than weakening, environmental governance. This requires greater support for civil society, broader environmental education, and more inclusive public participation in environmental decision-making. When citizens are informed and actively engaged, they are better able to pressure governments to prioritize long-term environmental protection over short-term political gains. Greater transparency in public institutions, media, and environmental reporting would further support this process.

Finally, closer cooperation among BRICS countries is essential. Because these economies face similar development and environmental challenges, they can benefit from sharing policy experiences, co-investing in green infrastructure, and harmonizing environmental standards. Stronger BRICS cooperation could facilitate the diffusion of environmentally beneficial technologies, encourage coordinated mitigation strategies, and improve collective resilience to environmental shocks.

7. Limitations and future research directions

Although this study provides important insights, several limitations should be acknowledged. First, because the analysis is limited to BRICS countries, the findings may not be fully generalizable to other groups of emerging economies. Future research could extend the analysis to countries such as the MINT economies, namely Mexico, Indonesia, Nigeria and Türkiye, allowing for broader comparative assessment and a deeper understanding of regional differences in environmental dynamics.

Second, while the ecological footprint is a comprehensive indicator of environmental pressure, it does not fully capture all dimensions of environmental degradation, such as biodiversity loss, freshwater quality, or specific forms of urban pollution. Future studies could therefore incorporate additional indicators, such as the Environmental Performance Index or other sustainability measures, to provide a more multidimensional assessment of environmental quality.

Third, the present analysis does not explicitly incorporate certain institutional factors that may strongly influence environmental outcomes, such as corruption, regulatory quality, or governance effectiveness. Including such variables in future research could provide a more complete explanation of how institutional conditions shape the effectiveness of environmental policy and technological adoption.

Fourth, although the MM-QR estimator effectively addresses heterogeneity, endogeneity, and individual and time effects, and provides valuable distributional insights, it does not explicitly capture possible nonlinearities or threshold effects in the relationships among variables. Future studies could therefore apply panel threshold models, spatial econometric techniques, or machine learning approaches to uncover more complex patterns in the environmental effects of economic, institutional, and technological factors.

Finally, this study is based primarily on quantitative analysis. Its findings could be enriched through qualitative methods, such as stakeholder interviews, policy case studies, or ethnographic evidence. A mixed-methods approach would be particularly useful for understanding why similar environmental policies produce different outcomes across BRICS countries despite comparable formal commitments.

Ethical statement

This study does not involve human participants or animals; therefore, ethical approval is not required.

CRediT authorship contribution statement

Imran Hossain: Writing – original draft, Project administration, Methodology, Conceptualization. **Mohammad Ridwan:** Writing – original draft, Software, Investigation, Formal analysis, Conceptualization. **Asif Raihan:** Writing – original draft, Validation, Resources. **Md. Mustaqim Roshid:** Writing – original draft, Validation. **Miguel Angel Esquivias:** Writing – review & editing, Supervision, Funding acquisition, Data curation. **Md. Emran Hossain:** Writing – original draft, Visualization, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data used in this research are publicly available. The sources are mentioned in Section 3.1 and Table 1.

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