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Energy Transition's Technical Pathways, Risks, and Equity—Article

The Effects of Energy Transition and Environmental Policy Stringency Subtypes on Ecological Footprint: Evidence from BRICS Countries via a KRLS Approach

Mustafa Tevfik Kartal [a,b,c,*], Arshian Sharif [d,e,f], Cosimo Magazzino [g,h], Shahriyar Mukhtarov [i,j,k,l], Dervis Kirikkaleli [m]

[a] Department of Finance and Banking, European University of Lefke, Mersin 99010, Türkiye
[b] Clinic of Economics, Azerbaijan State University of Economics (UNEC), Baku AZ1007, Azerbaijan
[c] Division of International Studies, Korea University, Seoul 02841, Republic of Korea
[d] Department of Economics and Finance, Sunway University, Bandar Sunway 47500, Malaysia
[e] University of Economics and Human Sciences in Warsaw, Warsaw 01-043, Poland
[f] College of International Studies, Korea University, Seoul 02841, Republic of Korea
[g] Economic Research Center (WCERC), Western Caspian University, Baku AZ1001, Azerbaijan
[h] ARUCAD Research Center, Arkin University of Creative Arts and Design, Mersin 99300, Türkiye
[i] Department of Economics, Korea University, Seoul 02841, Republic of Korea
[j] BEU-Scientific Research Center, Baku Engineering University, Khirdalan City AZ0101, Azerbaijan
[k] Research Center for Sustainable Economic Development, Khazar University, Baku AZ1096, Azerbaijan
[l] Azerbaijan University of Architecture and Construction, Baku AZ 1073, Azerbaijan
[m] Department of Economics, Adnan Kassar School of Business, Lebanese American University, Beirut 13-5053, Lebanon

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ABSTRACT

The world has been facing climate-related problems in recent decades, resulting from environmental degradation, making it increasingly critical to reduce environmental degradation in order to combat climate change. In this context, transforming economies into eco-friendly ones, ensuring the global energy transition from fossil-fuel-based power to renewable energy, and applying stringent environmental policies have been recent focus points of policymakers. Accordingly, this study analyzes the marginal effect of the energy transition, market- and non-market-based environmental policy stringency, and income on ecological footprint (EFP) in Brazil, Russia, India, China, and South Africa (BRICS) countries using data between 2000 and 2020 and applying a kernel-based regularized least-squares (KRLS) approach. The results show that ① economic growth has a stimulating marginal effect on EFP in BRICS countries except for Brazil, where it has an insignificant effect; ② energy transition efforts are ineffective in all countries, having the undesired effect of increasing EFP; ③ market-based environmental policies have a curbing effect on EFP in Brazil, Russia, and India but an increasing effect in China and an insignificant effect in South Africa; ④ non-market-based environmental policies are highly ineffective in all countries; ⑤ the KRLS approach exhibits excellent performance in the estimation of EFP, reaching approximately 99.61%; and ⑥ the marginal effect of the studied factors on EFP varies across factors, countries, and percentiles. Thus, this study highlights that BRICS policymakers should consider the marginal effects of the studied factors on EFP in combating environmental degradation and climate-related problems.

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1. Introduction

The environmental problems confronting humanity have worsened in recent years. While a variety of factors have influenced this issue, the use of various energy sources (i.e., fossil fuels) can be described as the most effective factor resulting in environmental degradation. The extraction, production, and consumption of such

* Corresponding author.
E-mail address: mustafatevfikkartal@gmail.com (M.T. Kartal).

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energy sources cause air pollution and, in turn, climate change. In particular, the burning of fossil fuels releases emissions and various harmful substances into the atmosphere that play a major role in global warming and climate change. From this point of view, dealing with environmental issues has become highly critical for all stakeholders in recent years.

In line with the increasing public awareness of environmental problems, research on this issue has developed extensively. In assessing environmental degradation, most previous studies have used carbon dioxide (CO_2) emissions as an indicator [1–3]. However, more recent studies have chosen to use the ecological footprint (EFP) as a more comprehensive indicator of environmental sustainability [4–7]. The EFP measures the amount of natural resources used to produce the goods consumed by a specific population and to absorb the waste they generate, using current technology [8]. It assesses the regenerative biological capacity demanded by human activities [9]. Such demands exert pressure on ecosystems through land-use changes, resource extraction and depletion, waste and pollution emissions, and the modification and movement of organisms [10]. In essence, the EFP provides a comprehensive measure of the multidimensional effects of human activities on the environment, making it a relatively accurate proxy for environmental sustainability.

In comparison with the behavior of developed countries, the behavior of emerging countries has become much more significant because these nations are in developing stages, use high levels of fossil fuel energy, and lack an eco-friendly economic growth structure. Therefore, it is crucial to focus on emerging countries in any examination of the global environment. In this context, it can be much more beneficial to consider a bundle of emerging countries instead of addressing the case of any single emerging country. Among the world's nations, BRICS countries (i.e., Brazil, Russia, India, China, and South Africa) are a leading emerging country group that collectively account for 41.75% of the world's greenhouse gas emissions [11] and approximately 26% of the global economy (World Bank (WB) [12]). Moreover, BRICS countries include leading emerging countries that have been facing critical environmental problems and are using large amounts of fossil fuel-based energy [13]. Therefore, BRICS countries constitute an appropriate sample for consideration in an empirical investigation of the key factors affecting EFP. Fig. 1 [14] illustrates EFP trends in BRICS countries. In this study, BRICS countries are referred to using shortened terms: BRA for Brazil, RUS for Russia, IND for India, CHN for China, and ZAF for South Africa.

Fig. 1 emphasizes notable increments in most countries from 2000 to 2020. ZAF's EFP shows a moderate increase, suggesting a decelerated rate of industrialization and use of resources. RUS and BRA have more volatility in their patterns, exhibiting peaks in 2011 and 2013, respectively, followed by subsequent falls. CHN and IND have the most significant expansion, indicating their rapid economic progress and population growth. Thus, Fig. 1 highlights the diverse environmental effects across the BRICS countries.

Environmental degradation is a pressing challenge for humanity. The environmental Kuznets curve (EKC) hypothesis [15] is a widely recognized theoretical framework for analyzing environmental degradation. The traditional EKC hypothesis suggests that there is an inverted U relationship between environmental degradation and income. The EKC offers a limited and implicit set of policy measures to combat pollution, as it typically associates pollution levels with income variations [16]. As a result, research has expanded pollution analysis to include additional factors (e.g., economic structure, energy consumption, trade openness, environmental policies, and globalization) [17], although many of these considerations lack theoretical justification [18]. While such factors are well-known in terms of their effects, it is now essential to investigate the effects of other factors (e.g., the energy transition and environmental policy measures) that have become more important during the energy crisis and public efforts.

In addition to environmental benefits, the transition to a low-carbon economy has the potential to generate good economic prospects. The act of investing in clean energy and eco-friendly technology within eco-friendly sectors can encourage new ideas, generate employment, and boost economic development. Fig. 2 [19] depicts the progress of the energy transition index (ETI) in BRICS countries.

As shown in Fig. 2, all countries experienced an increase in ETI during the studied period, with RUS and CHN achieving the highest ETIs as of 2020. BRA and ZAF show smaller, fluctuating changes, while IND consistently demonstrates an upward trend. Overall, these countries are advancing in their energy transition efforts.

In addition to energy transition, efficient governance of environmental policies is essential for effectively controlling EFP. Implementing policies that promote sustainable resource use, decrease emissions, and incentivize environmentally conscious behaviors may effectively minimize negative effects on the environment. For these reasons, research has focused on uncovering the effects of various regulatory measures (e.g., environmental taxes and emission trading systems) on environmental degradation (e.g., Ref. [20]).

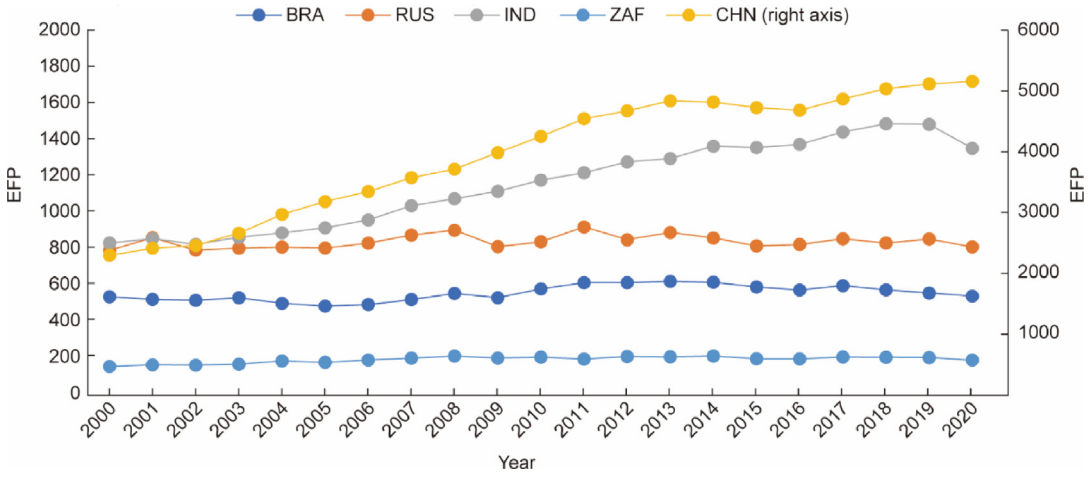

Fig. 1. Progress of EFP in BRICS countries, where BRA, RUS, IND, CHN, and ZAF respectively denote Brazil, Russia, India, China, and South Africa (unit: million global hectares) [14].

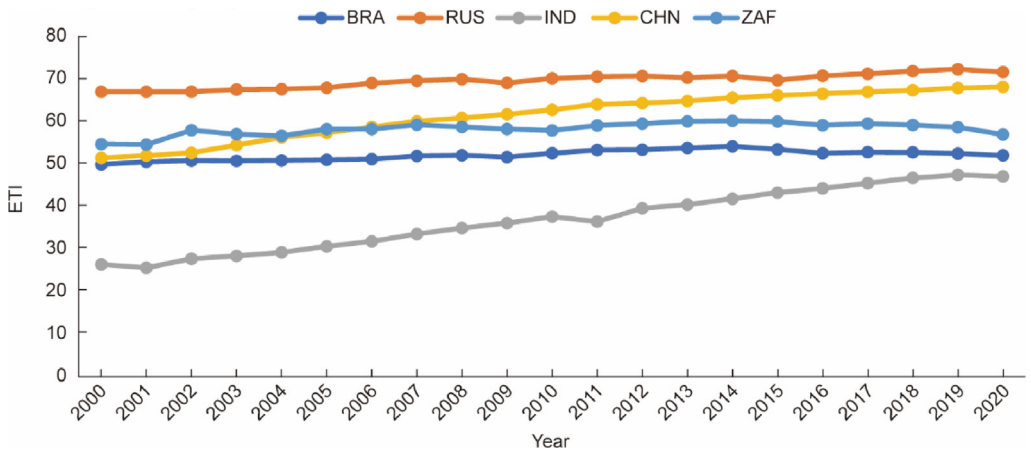

Fig. 2. Progress of the ETI in BRICS countries [19].

Stringent environmental policies incorporate strategies such as setting targets for reducing CO_2 emissions, implementing carbon pricing, and promoting energy efficiency [21]. Environmental policy stringency (EPS) is an indicator developed by the Organisation for Economic Co-operation and Development (OECD) that combines data on a range of environmental policies to create a comprehensive measure reflecting the comparative rigor of these policies [21,22]. These measures incentivize industries to embrace cleaner technologies, leading to a reduction in CO_2 emissions. The stringency of these policies is related to the level of enforcement required by the regulations [23]. The EPS index assesses the strictness of these policies, which may involve market-based policies (MBP) or non-MBP (NMBP) [21,24]. MBP include taxes on various gas emissions, trading schemes for CO_2, renewable and energy-efficiency certificates, feed-in tariffs, and deposit and refund schemes, while NMBP include standards on emission limit values and research and development (R&D) subsidies by the government [21]. A graphical expression of the EPS and its sub-components with their weights in the calculation is presented in Fig. 3 [21,22].

Given the increasing worldwide importance of implementing environmental measures, it is crucial to examine the effect of environmental policies on environmental degradation by considering two subtypes. However, EPS does not enable researchers to accurately determine the individual effects of MBP and NMBP—where the focus points of the measures are based on either market or non-market policies—on the environment. Therefore, this study treats both as separate variables to uncover their unique effects. Fig. 4 [25] demonstrates the progress in MBP in BRICS countries.

In Fig. 4, RUS demonstrates sustained engagement, showing a notable surge around 2013, while IND and CHN show steady increments. ZAF exhibits modest growth, while BRA maintains a relatively constant trend with few fluctuations. Hence, the BRICS countries have different degrees of dedication and effectiveness in implementing MBP. Fig. 5 [25] demonstrates the advancement of NMBP in BRICS countries.

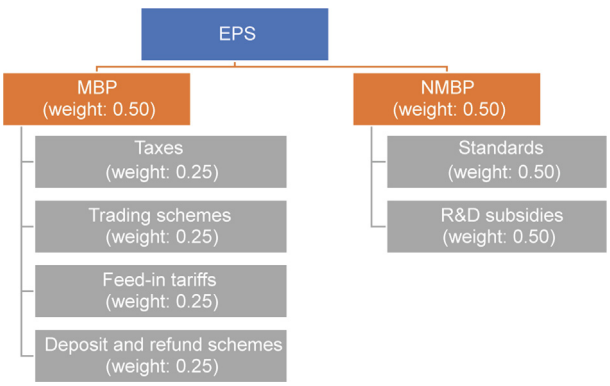

Fig. 3. Aggregation structure of EPS [21,22].

As shown in Fig. 5, BRA exhibits a consistent upward trend, reaching a value of 1.5 by 2016 and maintaining it thereafter. IND shows the highest and most continuous increase, going from a value of 2.00 in 2000 to 5.25 by 2020. RUS maintains a steady score of about 0.50. CHN and ZAF have generally consistent—albeit lower levels, with CHN's policy involvement exhibiting a minor rise post-2014. Collectively, the BRICS countries have varied strategies when it comes to NMBP.

Despite their attempts to reduce pollution and emissions, BRICS countries—especially CHN and IND—still have significant environmental problems [13]. Therefore, it is crucial to evaluate the role of the energy transition, stringent environmental policies, and income on the EFP in BRICS countries. Although the literature includes various studies on the ETI (e.g., Ref. [26]), aggregated-level EPS (e.g., Ref. [27]), and BRICS countries (e.g., Ref. [28]), there is a gap in the literature: No studies have examined the EFP in BRICS countries by uncovering the marginal effect of income, energy transition, and subtypes of EPS, and none have considered country-based differences by applying country-level analyses to address the heterogeneous economic and environmental characteristics, instead of using a panel approach. To address this literature gap, the present study aims to explore the following research questions:

(1) What are the effects of ETI, MBP, NMBP, and gross domestic product (GDP) on the EFP in BRICS countries?

(2) Are the effects linear or do they vary in the case of marginal increases in the factors?

(3) Are the effects the same in the case of the average marginal effect (AME) and pointwise marginal effect (PME) or do they change?

This study seeks to thoroughly examine the influence of the studied factors on EFP emissions in BRICS countries by using the KRLS approach. The results from a comprehensive and distinctive analysis indicate that GDP mainly has an increasing marginal effect, ETI and NMBP are completely inefficient, and MBP are mainly beneficial in lowering EFP.

In seeking new insights into these research questions, this study provides contributions to the literature by broadening the scope of knowledge. First, instead of focusing on the proportion of renewable energy use in the total energy mix, this study uses the ETI as an indicator of energy transition—an index that offers a comprehensive measure. Second, this study considers subtypes of EPS

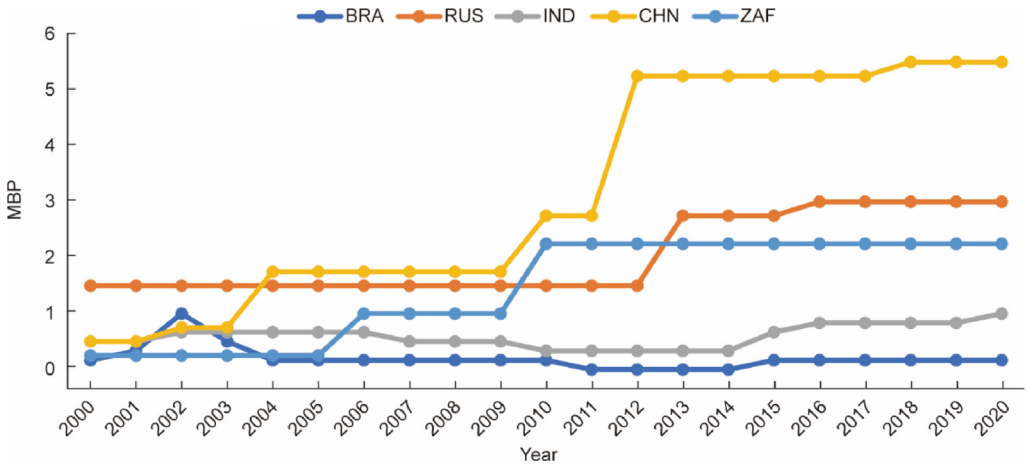

Fig. 4. Progress of MBP in BRICS countries [25].

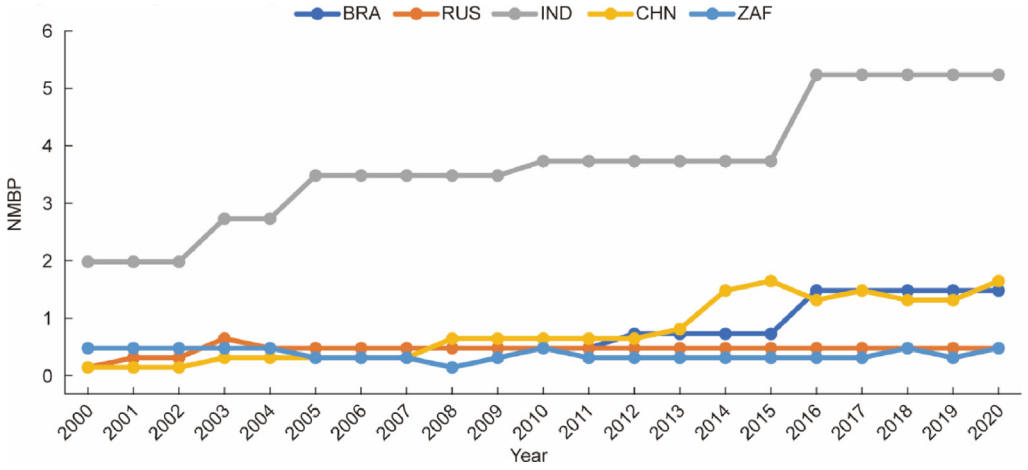

Fig. 5. Progress of NMBP in BRICS countries [25].

(i.e., MBP and NMBP), enabling researchers to assess the distinct effects of these types of policies individually. Third, this research provides a detailed marginal analysis. Thus, this study combines thorough theoretical and econometric elements.

In the remainder of this paper, Section 2 presents the theoretical background and empirical literature, Section 3 explains the methods used, Section 4 demonstrates the empirical results, and Section 5 concludes the paper.

2. Theoretical background and literature review

2.1. Theoretical underpinning

The seminal studies of Kraft and Kraft [29] on the energy-led growth hypothesis and of Grossman and Krueger [15] on the EKC hypothesis identify energy use and income structure as traditionally known factors critical for understanding the relationship among energy, income, and environment. Following these pioneering works, numerous studies have explored the environmental implications of various factors, including income and energy (e.g., Refs. [30–32]). Such studies have established that environmental degradation increases with an increase in non-eco-friendly economic growth—including high levels of fossil fuel-based energy use. Hence, while higher energy use supports economic growth, unfortunately, it does not contribute to eco-friendly economic growth and environmental protection.

While both income and energy remain as traditional factors in environmental degradation, recent research has begun to incorporate other novel factors (e.g., renewable energy, nuclear energy, environmental tax, emissions trading, and R&D investments) into investigations of environmental degradation. Although such factors have been helpful in building an understanding of potential causes of and solutions for environmental degradation, these indicators do not reflect the full scope of measures implemented by policymakers. For this reason, there is a need for more comprehensive indicators to proxy for governmental efforts, making the roles of indicators such as the ETI and EPS essential.

By promoting the transition toward clean energy sources, countries can ensure a decrease in the adverse effects of fossil fuel-based energy use and other sources of environmental degradation proxied by the EFP. This shift can contribute to a country's environmental sustainability by reducing its energy use and transforming its economic activities into eco-friendly ones [26]. Similarly, by establishing strict environmental policies, countries can force producers and consumers to follow eco-friendly practices in their production and consumption processes through the use of fewer resources. In this context, policymakers can consider focusing on either MBP or NMBP or on their combined use [21]. While MBP aim to decrease environmental degradation by means of direct

effects through the market mechanism, NMBP are intended to ensure a decrease in environmental degradation indirectly by promoting public consciousness of standards and supporting relevant R&D activities [22,33]. In these ways, both the ETI and EPS can help support a nation's environmental sustainability by promoting a decrease in its EFP.

As an important cause of environmental degradation, energy use must be aligned with climate change mitigation, and the transformation of energy use toward clean energy must address environmental concerns. To reduce fossil fuel dependence, countries have been seeking clean energy sources, reducing their CO_2 emissions, and supporting the transition to a sustainable energy and economic structure. Moreover, governments have increasingly been establishing regulations and taking concrete measures to mitigate climate change and resource scarcity in order to develop a infrastructure for green economic progress—particularly in the context of energy efficiency and consumption.

2.2. Empirical literature

2.2.1. EPS and the environment

There has been a growing focus on EPSs with the aim of preventing environmental degradation. Environmental regulation and outcomes have been in focus within the regulation–environment–outcomes relationship since a 1995 study by Porter and Linde [34]. To mitigate the devastating effects of environmental degradation, governments around the world must act and adopt stringent environmental policies.

Dechezleprêtre and Sato [35] have reported that stringent environmental policies can reduce pollution by promoting eco-friendly technologies and discouraging environmentally destructive ones. Wolde-Rufael and Mulat-Weldemeskel [36] investigated the effect of environmental taxation and an environmental stringency policy on CO_2 emissions in seven emerging economies using a panel augmented mean group estimator. They found EPS to be inversely related to CO_2 emissions, suggesting that it takes time for such policies to be effective. Moreover, their findings indicated a negative and significant relationship between CO_2 emissions and total environmental taxes. Afshan et al. [37] explored the effects of renewable energy, ecological innovation, and EPS on the EFPs of OECD countries using a panel approach. Their findings revealed that the EFPs of the OECD countries were reduced by increasing the energy transition, eco-innovation, and environmental policies. Moreover, their findings validated the EKC hypothesis. Wang et al. [38] explored the effect of EPS on CO_2 emissions in BRICS economies and concluded that CO_2 emissions could be significantly reduced through strict environmental policies. They also emphasized that renewable energy reduces CO_2 emissions, and the transition to renewable energy can be accelerated by strict regulations.

Recently, Bashir et al. [39] reported that EPS supports environmental sustainability in Group of Seven (G7) countries. Kartal et al. [33] examined the effect of EPS on sectoral CO_2 emissions in the European Union and stated that, at higher EPS quantiles, building-sector CO_2 emissions were decreased in France, the United Kingdom, and Italy. EPS reduced the CO_2 emissions generated by industrial combustion in France and Italy and curbed CO_2 emissions from the power sector in Germany, Spain, and France. In addition, in France and Germany, EPS decreased CO_2 emissions from the transport sector. Gibba et al. [40] reported that EPS had a reducing effect on EFP in Australia as well. Kartal et al. [41] analyzed G7 countries and concluded that EPS was beneficial for reducing the EFP in the United States but not in Japan, while it had varying effects in the remaining G7 countries.

Overall, while EPS can be generally evaluated as an effective tool for decreasing environmental degradation, as measured by various indicators, such as CO_2 and EFP, the literature remains inconclusive, and further empirical exploration of the effects of EPS on environmental progress is required.

2.2.2. Energy transition and the environment

The energy transition is critical in reshaping nations' energy consumption to meet their zero-carbon targets in order to preserve environmental sustainability and decarbonize the energy sector. Moreover, a transition to clean energy supports sustainable growth, lowers pollution levels, and reduces the ecological effects of human activity.

Bashir et al. [42] and Bashir et al. [43] investigated the effects of the energy transition and concluded that environmental degradation was negatively affected by energy transition in the top ten manufacturing countries and in BRICS. Ahmad et al. [44] explored the effects of climate-tech (i.e., technologies aimed at enabling decarbonization) and the energy transition on CO_2 emissions and concluded that the energy transition and environmental regulations reduced CO_2 emissions as effective controlling tools, mitigating environmental degradation. Wang et al. [45] reported that renewable energy had a curbing effect on CO_2 emissions.

In recent years, Bashir et al. [39] reported that renewable energy has had a positive effect on environmental sustainability in G7 countries. Dong et al. [46] examined the instruments employed by regulatory frameworks on environmental degradation and identified a positive correlation between energy transition regulation (i.e., coal resource tax reform) and the reduction of environmental degradation. They found that energy transition regulation had a significant effect on environmental degradation in the western region of China, but no significant effect in the eastern and central regions. The researchers emphasized that it is crucial to optimize the industrial structure to reduce environmental degradation through energy transition regulation. Wang et al. [47] examined the effects of the energy transition, ecological governance, and globalization on the environment in the top ten emitting countries and reported that the energy transition, ecological governance, and globalization collectively contributed to reducing CO_2 emissions. Wang et al. [48] determined that artificial intelligence had a decreasing effect on EFP but an increasing effect on the energy transition.

In sum, while the energy transition is beneficial in reducing environmental degradation, the literature shows that it is insufficient in some countries, indicating a need for new studies.

2.2.3. Income and the environment

The effects of uncontrolled long-term economic development on environmental degradation are important in today's world, driving an increase in research into the link between income and environmental degradation. Following a study by Grossman and Krueger [15], various studies have uncovered the effects of changes in income on the environment. Shafik and Bandyopadhyay [49] were the first to use panel data for 149 countries to examine the EKC hypothesis, and their findings indicated that the hypothesis was invalid.

According to Liu and Bae [50], who used the autoregressive distributed lag (ARDL) approach, economic expansion in CHN resulted in increased CO_2 emissions. Ahmad et al. [51] and Ahmad et al. [52] examined 22 emerging (G7) countries with a panel data approach and showed that an increase in GDP caused an increase in EFP. Chen et al. [53] used a quantile ARDL approach based on annual Chinese data between 1990 and 2020 to study the interaction of GDP with CO_2 emissions and concluded that GDP positively affected CO_2 emissions in CHN. According to Gupta et al. [54], the size of Bangladesh's EFP increased with economic growth. Peng et al. [55] and Xue et al. [56] determined the augmenting effect of GDP on CO_2 emissions in BRICS and France, respectively. A study by

Qayyum et al. [57] found that CO_2 emissions and GDP in IND were positively correlated.

In recent years, Magazzino [58] reported that an increasing GDP increased EFP in China. Wang et al. [45] stated that the increase in CO_2 emissions in OECD countries was a result of economic development. Yasin et al. [59] concluded that the EKC hypothesis was valid for BRICS countries, with increases in GDP reducing the EFP.

To sum up, it is possible to observe that a country's GDP can have an eco-friendly structure, such that its increase can contribute to preserving environmental sustainability. However, the current literature shows that this is not always valid, and the GDP structure can be harmful. Hence, there is still a need for new studies to uncover the effects of changes in GDP on the environment.

2.3. Evaluation of the literature

The contemporary literature on environmental progress has been developing, with increasing interest from stakeholders including countries, policymakers, societies, and the public. The recent literature uses a variety of indicators (e.g., CO_2 and EFP) and considers numerous explanatory variables that may be effective against environmental degradation. Current studies have analyzed various countries and country groups by applying a set of different analysis approaches (e.g., ARDL). Studies have considered the effects of ETI, EPS, GDP, and other factors on environmental degradation in various countries (e.g., China, Bangladesh, France, India, and G7). Nevertheless, no study has investigated the effects of GDP, ETI, and EPS on EFP for BRICS countries by considering the subtypes of EPS (i.e., MBP and NMBP) or by applying a marginal effect analysis. Hence, there is a gap in the literature. This study considers the effects of the ETI, MBP, NMBP, and GDP on the EFP in BRICS countries by applying the KRLS approach, which is superior to traditional regression estimators, to close this literature gap and allow researchers to capture the marginal effects of the studied factors.

3. Methods

3.1. Data and variables

To find clear answers to the research questions listed in the Section 1, this study takes BRICS countries as the focus of analysis, as members of a leading emerging country group that collectively account for almost half of the world's greenhouse gas emissions and about a quarter of the global economy [11,12]. These countries also use large amounts of fossil fuel-based energy [13] and are encountering critical environmental problems. Hence, BRICS represent a crucial case regarding the world's environmental condition. In line with the research objectives, this study uses the EFP as a more comprehensive indicator than CO_2 emissions. Also, in line with the empirical literature examined, this study considers the ETI, MBP, NMBP, and GDP as the explanatory variables.

We choose to consider subtypes of EPS because aggregated-level EPS use may have a misleading result, as certain policy types (i.e., market-based or non-market-based) may be beneficial for some countries but not for others. Overall, this study investigates the marginal effects of the GDP, ETI, MBP, and NMBP on EFP in BRICS countries. MBP include market-oriented environmental measures, such as taxes and trading schemes, whereas NMBP consider non-market-based environmental precautions, such as performance standards and R&D subsidies [21].

Yearly data from 2000 through 2020 was used because the available data on the ETI started in 2000 and ended in 2020. Thus, all the accessible data was used. Data on EFP, GDP, and ETI was collected from the Global Footprint Network (GFN) [14], WB [60], and the United Nations Conference on Trade and Development (UNCTAD) [19], respectively. Data on both MBP and NMBP was gathered from the OECD [25]. Table 1 [14,19,25,60] summarizes the variables.

3.2. Empirical procedure

Based on the variables summarized in Table 1, this study follows the empirical procedure demonstrated in Fig. 6.

Accordingly, descriptive statistics are examined first. Next, correlations between the variables are commented on. Third, nonlinearities of the variables through using the Broock–Dechert–Scheinkman–LeBaron (BDS) test are uncovered [61]. Lastly, the KRLS approach is used to analyze both the AME and PME of the factors on EFP, respectively [62].

A nonlinear KRLS approach was chosen for the empirical investigation, based on the data characteristics of the variables. A nonlinear approach can enable researchers to obtain much better empirical results than a linear approach by better estimating the underlying relationship between the dependent and independent variables if variables are nonlinear (e.g., Ref. [63]). As can be seen from the preliminary statistics, the variables in the present study are mainly nonlinear, making a nonlinear approach such as KRLS highly appropriate. Furthermore, the KRLS approach has no preconditions [62], which makes it superior to many conventional approaches (e.g., ARDL and ordinary least squares (OLS)-based ones). Importantly, the KRLS approach also differs from many traditional approaches in that it makes it possible to investigate the AME and PME of the variables. Most traditional approaches can present the empirical results only at the mean point, whereas the KRLS approach provides empirical results across various levels of the variables, as is the case in this study. For these reasons, this study applies the KRLS approach as a superior econometric approach for the empirical analysis.

3.3. Model specification

In the empirical investigation, Eq. (1) is applied to uncover the AMEs of the factors on EFP across the BRICS countries:

$$\mathrm{EFP} = f(\mathrm{GDP}, \mathrm{ETI}, \mathrm{MBP}, \mathrm{NMBP}) \tag{1}$$

Next, Eqs. (2)–(5) are applied to uncover the PME of each factor on EFP across the BRICS countries:

$$\mathrm{EFP} = f(\mathrm{GDP}) \tag{2}$$

$$\mathrm{EFP} = f(\mathrm{ETI}) \tag{3}$$

$$\mathrm{EFP} = f(\mathrm{MBP}) \tag{4}$$

$$\mathrm{EFP} = f(\mathrm{NMBP}) \tag{5}$$

Table 1
Variables.

Symbol	Measurement unit	Data source
EFP	Million global hectares	Ref. [14]
GDP	Billion USD (2015 constant)	Ref. [60]
ETI	Index	Ref. [19]
MBP	Index	Ref. [25]
NMBP	Index	Ref. [25]

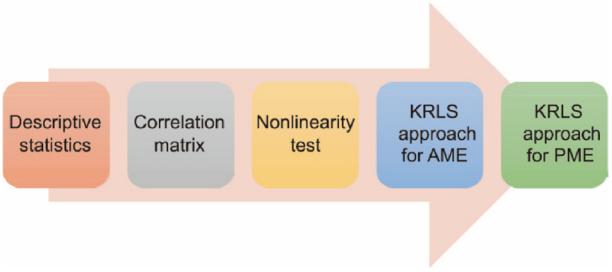

Fig. 6. Empirical procedure followed in this study.

By performing the KRLS approach on Eqs. (1)–(5), this study investigates both the AMEs and PMEs of the studied factors on EFP.

4. Empirical results

4.1. Preliminary statistics

Table S1 in Appendix A presents the descriptive statistics of the variables. GDP has the highest mean value and greatest variation among all variables in all countries. Also, GDP is followed by EFP in all countries in terms of having high mean values and variations. In some countries (i.e., RUS, CHN, and ZAF), the variations in MBP are greater than those in NMBP, whereas the variations in NMBP are greater than those in MBP in the remaining countries (i.e., BRA and IND). Moreover, all variables in the BRICS countries have a normal distribution except for MBP in BRA and NMBP in RUS. Hence, some variables (i.e., GDP and EFP) have more variations, and most of the variables have a normal distribution.

Table S2 in Appendix A reports the correlations between the variables. In BRA, EFP has a positive correlation with GDP and an ETI of over 0.8, as well as NMBP around 0.3. On the other hand, EFP is negatively correlated with MBP, with a correlation of around −0.5. In RUS, IND, and CHN, EFP has a complete correlation with the explanatory variables (i.e., GDP, ETI, MBP, and NMBP), where the correlations vary from 0.05 to 0.97 across the variables and countries. In ZAF, EFP is positively correlated with GDP, ETI, and MBP with correlations ranging from 0.77 to 0.86, whereas it is negatively correlated with NMBP, with a correlation of around −0.62.

Table S3 in Appendix A reports the correlations between the variables. In BRA and ZAF, all variables except for NMBP have a nonlinear structure, whereas NMBP have a mixed structure in BRA and a linear structure in CHN. In RUS, all variables except for EFP and NMBP have a nonlinear structure, whereas EFP has a linear structure and NMBP a mixed one. In IND and CHN, all variables are nonlinear.

In summary, across the countries, the studied variables exhibit high variation; they are generally normally distributed, although some have a non-normal distribution; there are various levels (i.e., low and high) of correlation between variables; and the variables are mainly nonlinear, although some are either mixed or linear. In such a case, where the variables have different characteristics, using a nonlinear approach can provide much better estimation results than a linear approach [63]. Therefore, this study applies a KRLS approach for the empirical analysis to gather estimation coefficients for AME and PME across the levels of the variables.

4.2. KRLS results

Following the examination of preliminary statistics, the AMEs of the variables on EFP are examined for the BRICS countries. Table 2 presents the KRLS results for BRA.

According to Table 2, ETI and MBP have a statistically significant effect on EFP in BRA. More specifically, ETI has an inefficient (i.e., increasing) effect on EFP. In contrast, MBP have a decreasing effect on EFP. Among the influential factors, MBP has a much stronger effect than ETI. Moreover, GDP and NMBP have an insignificant effect on EFP. Hence, it can be concluded that BRA can rely further on MBP for curbing EFP, but BRA does not have a good energy transition framework to decrease its EFP. Also, the factors considered have a high estimation power, reaching 98.10%. These results show that the economic growth structure, energy transition framework, and NMBP are not beneficial for BRA; only MBP are helpful to sustain BRA's environmental policy by decreasing EFP. Table 3 reports the KRLS results for RUS.

According to Table 3, all variables except for NMBP have a statistically significant effect on EFP for RUS. In detail, GDP and ETI have an inefficient (i.e., increasing) effect on EFP, whereas MBP have a decreasing effect on EFP. Among the effective factors, MBP have the largest and most decreasing effect, while ETI and GDP come next with increasing effects that are the smallest. NMBP have an insignificant effect on EFP. Therefore, it can be concluded that RUS can rely on MBP for decreasing its EFP, but the remaining factors do not help RUS to curb its EFP. Furthermore, the studied factors have a relatively low estimation power of around 38.15%. These results imply that RUS can only benefit from MBP for decreasing its EFP; the current economic growth structure, energy transition framework, and NMBP are not helpful for environmental sustainability in RUS. Table 4 demonstrates the KRLS results for IND.

According to Table 4, all the studied factors have a statistically significant effect on EFP in IND. Among the factors, only MBP have a decreasing effect on EFP. On the other hand, the remaining factors (i.e., GDP, ETI, and NMBP) have an inefficient (i.e., increasing) effect on EFP. Moreover, the factors included have a high estimation power, reaching 99.61%. Overall, it is clear that IND should construct its environmental policies by further relying on MBP, while there is a need for urgent restructuring in IND's GDP, ETI, and NMBP to make these factors beneficial for protecting the country's environmental sustainability. Table 5 shows the KRLS results for CHN.

According to Table 5, all factors excluding NMBP have a statistically significant effect on EFP in CHN. While all the other factors (i.e., GDP, ETI, and MBP) have an inefficient (i.e., increasing) effect on EFP, MBP have a much stronger effect than the rest. Also, the model has high estimation power, reaching 99.32%. These results show that the studied factors are not beneficial for curbing EFP in CHN. This finding implies the need for an urgent transformation in CHN's economic growth structure, energy transition framework, MBP, and NMBP to make these key factors beneficial for environmental sustainability. Table 6 presents the KRLS results for ZAF.

According to Table 6, both GDP and ETI have a statistically significant and increasing effect on EFP in ZAF. MBP and NMBP are inefficient (i.e., have an insignificant effect) in decreasing EFP. Moreover, the studied factors have a high estimation power, reaching 94.54%. Hence, it can be concluded that ZAF should restructure its environmental policy by considering the inefficiency of the studied factors; similar to CHN, ZAF cannot benefit from the factors of GDP, ETI, MBP, or NMBP in protecting its environmental sustainability by decreasing its EFP.

4.3. PME results

As the last step in the empirical analysis, the PMEs of the variables on EFP are examined across the BRICS countries. Fig. 7 presents the PME results for BRA.

According to Fig. 7, GDP has a positive PME on EFP across the low and medium levels of EFP in BRA. However, the PME of GDP

Table 2
KRLS results for BRA.

Variable	AME	SE	*t*-statistics	*P* value > *t*	P25	P50	P75
GDP	0.0050	0.0160	0.3120	0.7590	−0.0509	−0.0316	0.0400
ETI	14.8634	2.9195	5.0910	0.0000	−0.6369	9.9789	35.8572
MBP	−33.0537	13.7799	−2.3990	0.0280	−59.9159	−45.0813	1.0142
NMBP	−5.4330	3.7954	−1.4310	0.1700	−14.3890	−4.6970	1.8048

SE: standard error; P25, P50, and P75: the 25th, 50th, and 75th percentiles; coefficients of determination R^2 = 98.10.

Table 3
KRLS results for RUS.

Variable	AME	SE	*t*-statistics	*P* value > *t*	P25	P50	P75
GDP	0.0191	0.0071	2.7050	0.0150	−0.0032	0.0056	0.0425
ETI	2.8702	1.6207	1.7710	0.0940	−0.3789	1.2687	5.9863
MBP	−6.1177	2.8393	−2.1550	0.0460	−14.6429	−0.6376	−0.5531
NMBP	−4.2303	11.8435	−0.3570	0.7250	−9.6723	−3.2961	−0.6296

R^2 = 38.15.

Table 4
KRLS results for IND.

Variable	AME	SE	*t*-statistics	*P* value > *t*	P25	P50	P75
GDP	0.1390	0.0108	12.8820	0	0.0939	0.1481	0.2068
ETI	9.0957	0.9436	9.6390	0	4.1284	9.1125	13.3042
MBP	−154.1490	30.6096	−5.0360	0	−322.1000	−268.6810	59.7656
NMBP	18.8672	5.1189	3.6860	0.0020	−9.0202	15.4396	46.6775

R^2 = 99.61.

Table 5
KRLS results for CHN.

Variable	AME	SE	*t*-statistics	*P* value > *t*	P25	P50	P75
GDP	0.0612	0.0064	9.5010	0	0.0457	0.0681	0.0839
ETI	51.5886	3.9208	13.1580	0	16.3002	25.6174	93.3286
MBP	88.0252	17.5760	5.0080	0	18.5256	36.0936	190.9390
NMBP	72.7104	80.6264	0.9020	0.3800	−4.3317	104.3910	222.2520

R^2 = 99.32.

Table 6
KRLS results for ZAF.

Variable	AME	SE	*t*-statistics	*P* value > *t*	P25	P50	P75
GDP	0.1689	0.0515	3.2790	0.0040	−0.0343	0.0685	0.3967
ETI	2.4143	1.2580	1.9190	0.0720	0.5278	2.7428	4.2749
MBP	−2.0744	1.9672	−1.0540	0.3060	−7.7990	−3.5071	3.7600
NMBP	11.1605	12.2251	0.9130	0.3740	−7.1938	20.8348	26.2512

R^2 = 94.54.

on EFP becomes negative at a high level of EFP. This finding implies that increasing the GDP has a stimulating effect on EFP in the initial stages. However, at higher levels of EFP, GDP has a decreasing effect. Also, ETI has an almost completely positive effect on EFP across all levels, whereas the increasing effect is much stronger at a medium level of EFP. In contrast, the PME of MBP on EFP is positive at low levels and becomes negative at medium and high levels of EFP. On the other hand, the PME of NMBP on EFP is negative at low and medium levels and becomes positive at high levels of EFP. These determinations show that BRA can benefit most from MBP in decreasing its EFP, followed by NMBP, whereas ETI and GDP do not help preserve BRA's environmental sustainability by reducing EFP. Fig. 8 shows the PME results for RUS.

According to Fig. 8, GDP and ETI have almost completely positive PMEs on EFP in RUS. While the PME is negative at a low level, it becomes positive across medium and high levels of EFP in terms of the effects of both GDP and ETI. These findings show the inefficient contribution of GDP and ETI in decreasing EFP. On the other hand, in the case of the PMEs of MBP and NMBP, there is a positive effect at low levels and a negative effect at medium and high levels of EFP. Also, the negative PME of MBP is much stronger at a medium level of EFP. In this way, it is clear that MBP and NMBP help decrease EFP in RUS, but this is not the case for GDP and ETI. Fig. 9 demonstrates the PME results for IND.

According to Fig. 9, GDP, ETI, and NMBP have almost fully positive PMEs on EFP. While the PMEs of both GDP and ETI are completely positive, the PME of NMBP becomes negative at a high level of EFP. On the other hand, the PME of MBP on EFP is fully negative, while the decreasing effect is much more powerful at higher levels of EFP. Hence, the findings show that IND can benefit from MBP in moving its EFP into a declining pathway. Fig. 10 shows the PME results for CHN.

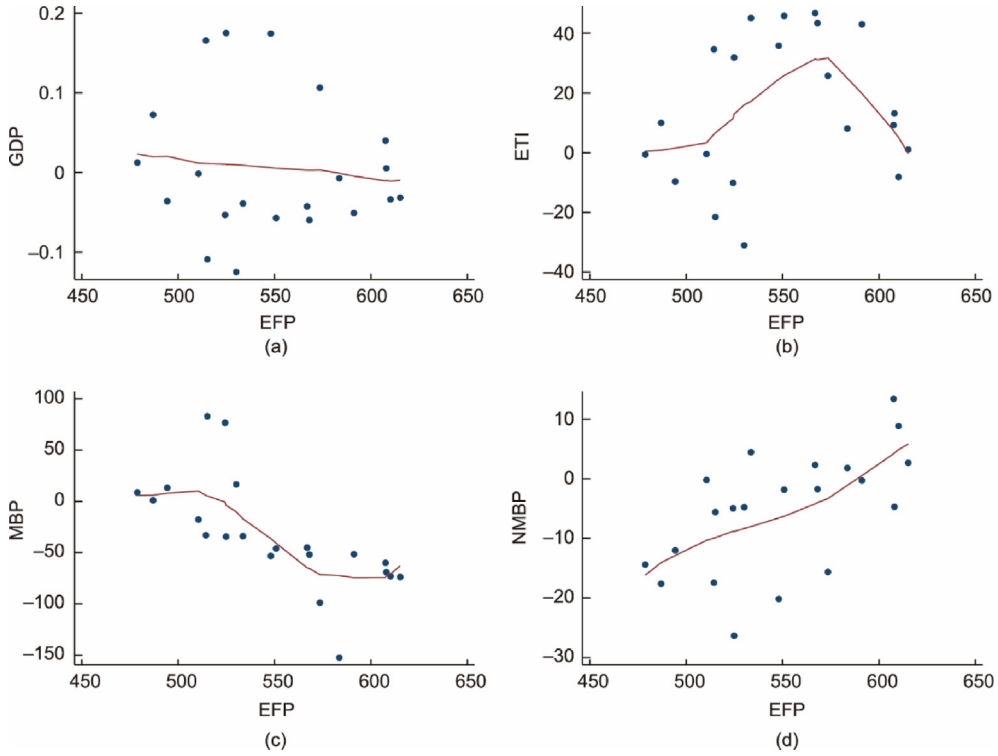

Fig. 7. PME results of (a) GDP, (b) ETI, (c) MBP, and (d) NMBP on EFP for BRA.

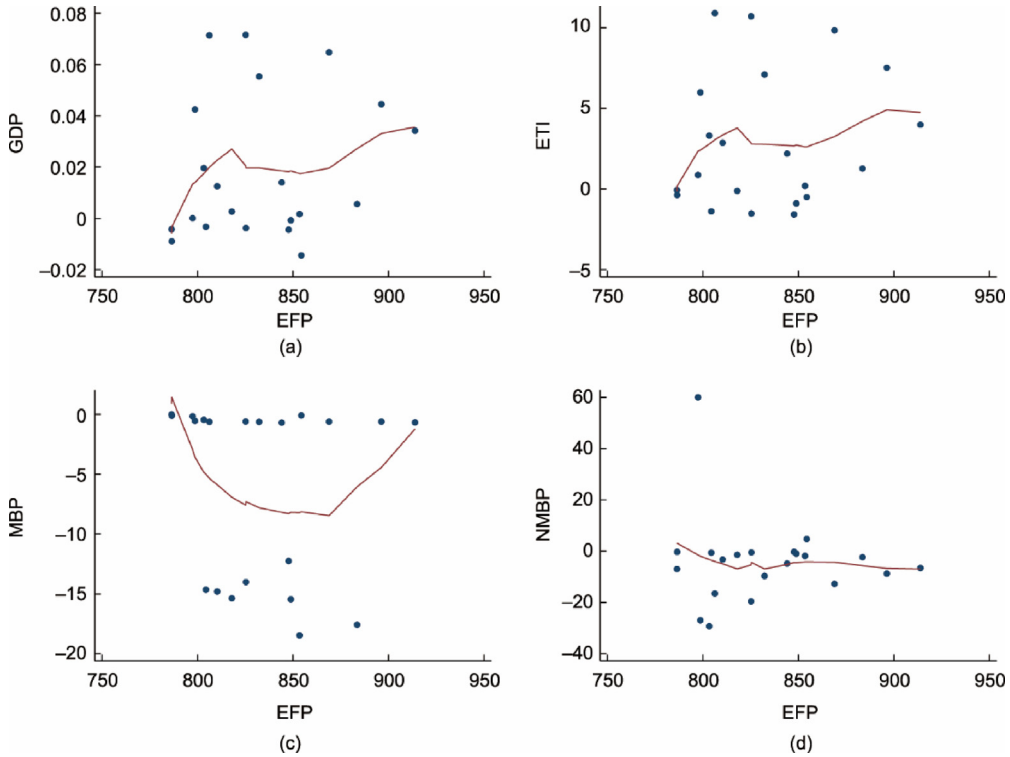

Fig. 8. PME results of (a) GDP, (b) ETI, (c) MBP, and (d) NMBP on EFP for RUS.

According to Fig. 10, all factors have completely positive PMEs on EFP across the levels. Among the factors, GDP, ETI, and MBP have inverse U-shaped PMEs on EFP, whereas NMBP have an N-shaped PME across the levels of EFP. These results imply that all these factors have an increasing effect on EFP in CHN, so CHN cannot benefit from these factors in reducing its EFP. Fig. 11 presents the PME results for ZAF.

According to Fig. 11, both GDP and NMBP have almost fully positive PMEs on EFP across the levels of EFP in ZAF. On the other hand, ETI has a negative (positive) PME on EFP across low (medium

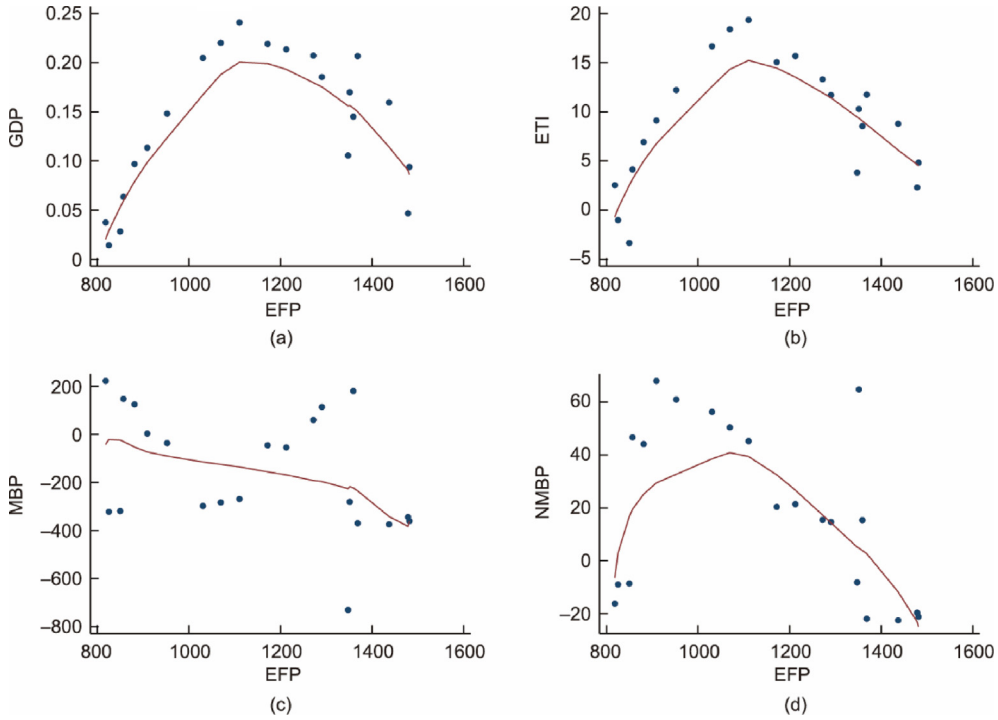

Fig. 9. PME results of (a) GDP, (b) ETI, (c) MBP, and (d) NMBP on EFP for IND.

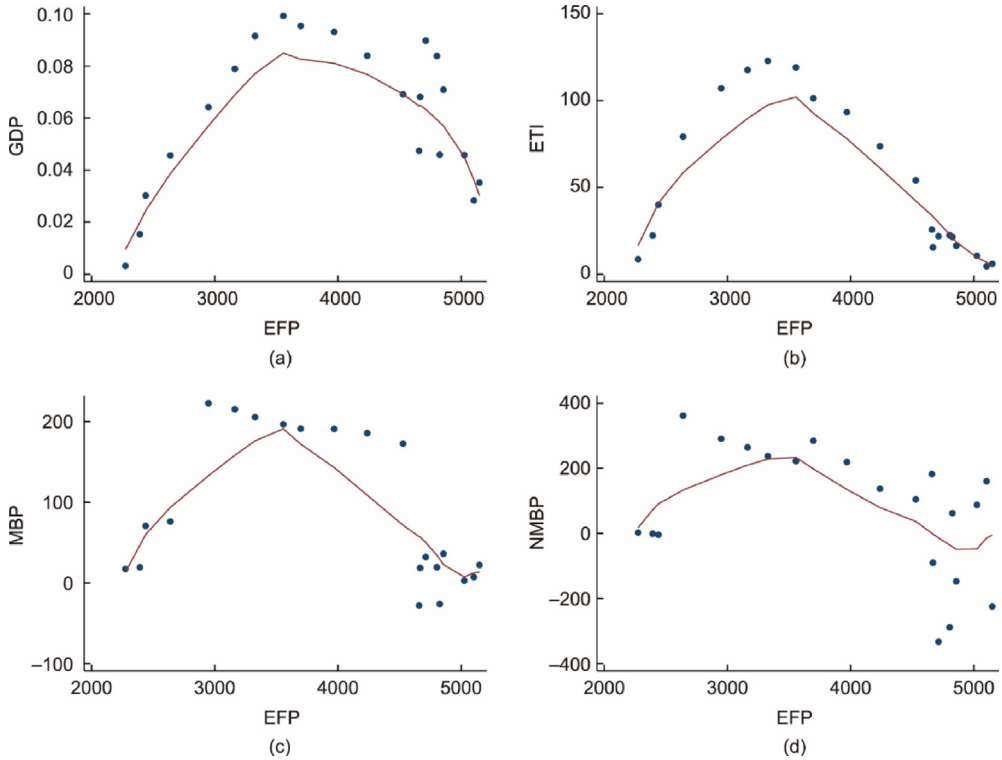

Fig. 10. PME results of (a) GDP, (b) ETI, (c) MBP, and (d) NMBP on EFP for CHN.

and high) levels of EFP. In contrast, MBP has a positive (negative) PME on EFP across low and medium (high) levels of EFP. Hence, ZAF can benefit from MBP at higher levels, but there is no room for growth for other factors in this respect.

4.4. Summary of the empirical results

Table 7 summarizes the empirical results gathered from the KRLS approach. According to Table 7, GDP has an insignificant

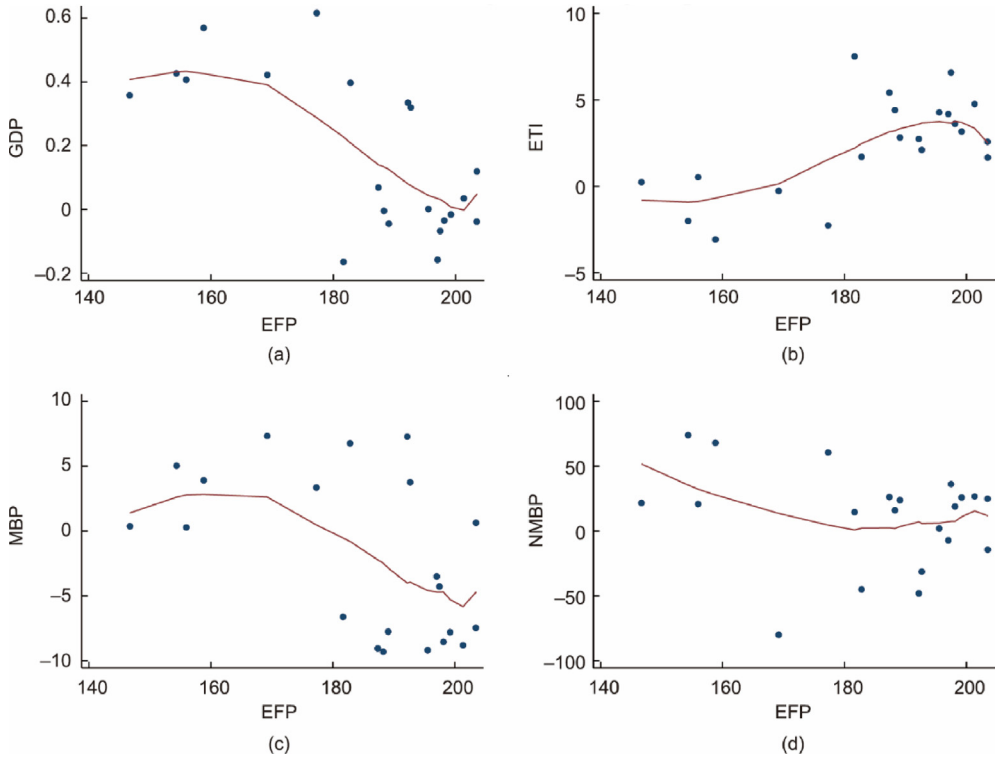

Fig. 11. PME results of (a) GDP, (b) ETI, (c) MBP, and (d) NMBP on EFP for ZAF.

Table 7
Summary of the results.

Country	Variable				R^2
	GDP	ETI	MBP	NMBP	
BRA	IS	+	–	IS	98.10
RUS	+	+	–	IS	38.15
IND	+	+	–	+	99.61
CHN	+	+	+	IS	99.32
ZAF	+	+	IS	IS	94.54

+, –, and IS respectively represent increasing, decreasing, and insignificant effects, respectively.

AME on EFP in BRA, whereas there is a positive (i.e., increasing) AME of GDP on EFP in the remaining countries. Hence, it is clear that none of the BRICS countries have an eco-friendly economic growth structure. Also, ETI has completely insignificant (i.e., increasing) AMEs on EFP in all BRICS countries. Therefore, BRICS countries do not have a good energy transition policy framework to benefit from to decrease their EFP. MBP have a decreasing effect on EFP in BRA, RUS, and IND, while the reverse is true for CHN and MBP have an insignificant AME for ZAF. These findings imply that only BRA, RUS, and IND have good MBP for protecting the environment. Moreover, NMBP have insignificant AMEs on EFP across all countries except for IND, where NMBP have an increasing effect. This finding demonstrates that no BRICS countries have good structured NMBP to ensure environmental sustainability.

5. Conclusions, policy caveats, and further research

5.1. Conclusions and discussion

Interest in environmental issues has been developing worldwide with the increasing adverse effects of climate change affecting humanity, and policymakers have been searching for potential solutions. Across the world, developed countries are playing a leading role in carrying out a green transformation to ensure environmental sustainability. However, the case of developing countries has recently come to the forefront, and a focus on leading emerging countries is essential in slowing down climate-related problems by ensuring global environmental sustainability.

The BRICS countries have been experiencing rapid economic growth, making them significant contributors to environmental degradation. Therefore, reducing environmental degradation in the BRICS countries has become an important point for meeting sustainable development goals across the world. To address this issue, this study explored the effects of GDP, ETI, MBP, and NMBP on EFP in BRICS countries by utilizing the KRLS approach.

The empirical investigation results indicate that GDP has a positive marginal effect on EFP in all BRICS countries except BRA, where its effect is statistically insignificant. This finding is consistent with the results of Ahmad et al. [51], Ahmad et al. [52], Chen et al. [53], Peng et al. [55], and Wang et al. [45], respectively, regarding 22 emerging countries, the G7, China, Colombia, BRICS, and OECD, as these scholars report similar results for mean-based effects of GDP on environmental sustainability.

Both ETI and NMBP are ineffective across all countries, leading to an increase in EFP. This finding strongly aligns with the studies of Kartal et al. [26] and Kartal et al. [27] for the cases of the United States and of Finland and Sweden, where the effects of ETI and EPS have a varying structure across the levels of the factors. MBP reduce EFP in BRA, RUS, and IND, but cause an increase in CHN and have no significant effect in ZAF. These findings generally align with those of Kartal et al. [27] for the case of the Finland and Sweden, where the effect of EPS was shown to have a differentiating structure across the quantiles. The KRLS approach was found to be highly successful in estimating EFP, with an accuracy of approximately 99.61%. Thus, the empirical results revealed that the AME

and PME of GDP, ETI, MBP, and NMBP on EFP differ according to the factors, countries, and percentiles.

The results of this study are generally consistent with the present literature. Nevertheless, this study contributes to the current body of knowledge by presenting fresh insights into the percentile-based varying effects of GDP, ETI, MBP, and NMBP on EFP. In achieving this, the study uses a novel indicator, the ETI; considers subtypes of EPS (i.e., MBP and NMBP) to avoid causing misleading results by using aggregated-level EPS; and applies the KRLS approach to perform a marginal effect analysis.

5.2. Policy caveats

Using the KRLS approach, this study presents the effects of ETI, MBP, NMBP, and GDP on EFP in BRICS countries. This allows various policy caveats to be discussed for the consideration of policymakers in BRICS while relying on empirical results.

Among MBP and NMBP, MBP have a curbing effect on EFP in BRA, RUS, and IND. On the other hand, NMBP are not efficient in all the BRICS countries. Hence, BRA, RUS, and IND have the opportunity to rely on further MBP for decreasing their EFP, whereas no BRICS countries can benefit from NMBP for decreasing their EFP. These findings imply that market-based environmental policies (e.g., taxes and trading schemes) have a much more powerful and beneficial effect than non-market-based environmental policies (e.g., emission limits and R&D investments). Accordingly, BRICS countries must rely on explicit rather than implicit environmental policies to ensure a decrease in their EFP, because of the beneficial effect of explicit policies. Accordingly, BRICS countries should focus on better managing their market-based environmental policies. Also, BRICS policymakers should rework the current NMBP framework, try to find out why these policies are not working in these countries, and think about either taking additional measures or replacing these measures with MBP ones. Hence, the BRICS countries can benefit from stringent environmental policies when taking appropriate actions in the correct area (i.e., MBP or NMBP).

The findings show that the economic growth structure of the BRICS countries is not eco-friendly. Therefore, BRICS policymakers must work on the economic growth cycles of their economies so that they can apply economic, energy, and environment-related policies to create a path for their economies to transform into eco-friendly ones. In this context, BRICS policymakers can consider various measures, such as taxing dirty technology use and fossil fuel energy consumption, supporting the electrification of the economic sector, and trying to shift producers' and consumers' attitudes toward eco-friendly production and consumption behaviors by relying on environmental and other organizations to conduct public awareness campaigns and various subsidies. By achieving a conversion of their economic growth structure through such policies, while considering the appropriateness of such measures for own conditions, it is possible for BRICS countries to decrease their EFP.

According to the findings, the current energy transition frameworks of BRICS countries are ineffective and cannot lead to a decrease in EFP. This means that the BRICS countries have failed to ensure an energy transition to clean sources through their transition policies and efforts. To address this issue, the BRICS countries should restructure their energy transition policies. First, they should examine their current energy mix to determine the share of each energy source. Next, they should determine which non-eco-friendly energy sources can be displaced with alternative clean energy sources (e.g., hydro, solar, wind, and nuclear), where feasible. Then, they should apply taxes and extra charges on fossil fuel sources while simultaneously applying discounts, subsidies, and incentives for the use of the clean energy sources they want to support further. The energy transition in BRICS countries can be stimulated by other economic measures, such as electrification of the economic sector and the use of electricity-based cars and trains, which will promote clean energy use. Moreover, these countries should consider potential displacement between clean energy sources and ensure that there is no displacement effect among clean energy alternatives that may affect the use of multiple sources of clean energy. In this way, they can create an efficient energy transition pathway that holds the potential to be effective and to have a curbing effect on EFP.

The results show that, although the studied countries are categorized within the same country block (i.e., BRICS), there are certain differences across countries. To be specific, BRA, RUS, and IND have similar cases, with MBP being beneficial and the remaining factors (i.e., GDP, ETI, and NMBP) being unhelpful. In contrast, both CHN and ZAF have no opportunity to benefit from any of the studied factors. These findings show the critical importance of considering country-based conditions when policymakers aim to reshape economic, energy, and environment-related policies.

In the marginal effect analysis, the KRLS approach provided successful estimation results reaching 99.61%. Moreover, the KRLS results revealed the nonlinear effects of the factors on EFP, while the effects varied across percentiles of the factors. Thus, it is essential to consider the nonlinear structure of the factors' effects as well as their differentiating effects across the levels of the factors in terms of a country's progress with its EFP. When applying straightforward policies that follow a linear approach, it is not always possible to obtain good results, as the factors' effects may have a nonlinear structure. In addition, because the effects change across thresholds, it is important to install a continuous monitoring mechanism to take measures in a timely manner without delay, since the variables' effects change before and after such thresholds. Neglecting these points (i.e., nonlinearity and thresholds) would make it impossible to apply a robust and appropriate policy framework.

5.3. Limitations and directions for further research

This study has attempted to carry out a comprehensive analysis. Although this effort was made, there were some limitations. The first limitation is related to scope. Since this study focused on analyzing BRICS countries, new studies can examine additional developing countries in their empirical analyses. New studies could also focus on developed countries. Moreover, both developed and developing countries could be investigated comparatively.

The second limitation is related to the explanatory variables. While this study focused on the effects of the GDP, ETI, MBP, and NMBP on EFP, new studies can consider either examining other factors or extending the scope of the explanatory variables by including much newer variables in addition to those used herein. In this context, new studies can evaluate the roles of political stability, institutional quality, and geopolitical risk as recently emerged factors that may influence EFP.

The third limitation is related to the dependent variable. While this research uses the EFP, new research can either include other variables or consider the simultaneous use of multiple factors, allowing various aspects of the environment to be considered in the same study.

The fourth limitation is related to the econometric approach used. This study used the KRLS approach to investigate the marginal effects of the variables. Naturally, the effects change not only across percentiles but also across times, frequencies, and quantiles. Thus, future research can consider applying time- and frequency-based approaches as well as quantile-based ones.

The last limitation is related to the dataset used. Because the OECD [25] provided data that ended in the year 2020, it was not

possible to consider the recent years from 2021 to today. Thus, as soon as new data is published by the OECD [25], new studies will be able to include much newer data. Due to critical events during this uncovered period, such as the global pandemic, new studies can also consider potential structural breaks in econometric analysis. In this respect, other econometric approaches that consider structural breaks can be applied in new studies.

By considering the above-stated issues in the formulation of new investigations, future research can examine various aspects of the environment through empirical analysis. Hence, the knowledge presented here can be extended further, and new policy options can be discussed for BRICS countries based on new determinations.

CRediT authorship contribution statement

Mustafa Tevfik Kartal: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Arshian Sharif:** Writing – review & editing. **Cosimo Magazzino:** Writing – original draft. **Shahriyar Mukhtarov:** Writing – original draft. **Dervis Kirikkaleli:** Writing – original draft.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2025.02.007.

References

[1] Tamazian A, Rao BB. Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies. Energy Econ 2010;32(1):137–45.
[2] Apergis N, Payne JE. The emissions, energy consumption, and growth nexus: evidence from the commonwealth of independent states. Energy Policy 2010;38(1):650–5.
[3] Khan H, Liu W, Khan I, Oanh LK. Recent advances in energy usage and environmental degradation: does quality institutions matter? A worldwide evidence. Energy Rep 2021;7:1091–103.
[4] Mrabet Z, Alsamara M. Testing the Kuznets curve hypothesis for Qatar: a comparison between carbon dioxide and ecological footprint. Renew Sustain Energy Rev 2017;70:1366–75.
[5] Ulucak R, Bilgili F. A reinvestigation of EKC model by ecological footprint measurement for high, middle and low income countries. J Clean Prod 2018;188:144–57.
[6] Li R, Hu S, Wang Q. Reexamining the impact of natural resource rent and corruption control on environmental quality: evidence from carbon emissions and ecological footprint in 152 countries. Nat Resour Forum 2024;48 (2):636–60.
[7] Wang Q, Wang X, Li R, Jiang X. Reinvestigating the environmental Kuznets curve (EKC) of carbon emissions and ecological footprint in 147 countries: a matter of trade protectionism. Hum Soc Sci Commun 2024;11(1):160.
[8] Hoekstra AY. Human appropriation of natural capital: a comparison of ecological footprint and water footprint analysis. Ecol Econ 2009;68 (7):1963–74.
[9] Kitzes J, Wackernagel M. Answers to common questions in ecological footprint accounting. Ecol Indic 2009;9(4):812–7.
[10] Rudolph A, Figge L. Determinants of ecological footprints: what is the role of globalization? Ecol Indic 2017;81:348–61.
[11] GHG emissions of all world countries. Report. Emissions Database for Global Atmospheric Research; 2023.
[12] World development indicator [database]. Washington, DC: World Bank Group; 2023.
[13] Data for CO_2 emissions. Report. London: Energy Institute; 2024.
[14] Data of ecological footprint. Report. Oakland: Global Footprint Network; 2024.
[15] Grossman GM, Krueger AB. Environmental impacts of a North American free trade agreement. NBER Working Paper 1991;3914.
[16] Hasanov FJ, Khan Z, Hussain M, Tufail M. Theoretical framework for the carbon emissions effects of technological progress and renewable energy consumption. Sustain Dev 2021;29(5):810–22.
[17] Shahbaz M, Hye QMA, Tiwari AK, Leitão NC. Economic growth, energy consumption, financial development, international trade and CO_2 emissions in Indonesia. Renew Sustain Energy Rev 2013;25:109–21.
[18] Hasanov FJ, Mukhtarov S, Suleymanov E. The role of renewable energy and total factor productivity in reducing CO_2 emissions in Azerbaijan. Fresh insights from a new theoretical framework coupled with autometrics. Energy Strateg Rev 2023;47:101079.
[19] Data of energy transition. Geneva: United Nations Trade and Development; 2024.
[20] Frohm E, D'Arcangelo FM, Kruse T, Pisu M, Sila U. Environmental policy stringency and CO_2 emissions: evidence from cross country sector-level data. OECD Working Papers 2023:1773.
[21] How stringent are environmental policies? Report. Paris: Organization for Economic Co-operation and Development; 2016.
[22] Botta E, Koźluk T. Measuring environmental policy stringency in OECD countries: a composite index approach. Report. Paris: Organization for Economic Co-operation and Development; 2014.
[23] Mihai DM, Doran MD, Puiu S, Doran NM, Jianu E, Cojocaru TM. Managing environmental policy stringency to ensure sustainable development in OECD countries. Sustainability 2023;15(21):15427.
[24] Chen M, Sohail S, Majeed MT. Revealing the effectiveness of environmental policy stringency and environmental law on environmental performance: does asymmetry matter? Environ Sci Pollut Res Int 2022;29(60):91190–200.
[25] Data of MBP and NMBP. Paris: Organization for Economic Co-operation and Development; 2024.
[26] Kartal MT, Taşkın D, Shahbaz M, Kirikkaleli D, Depren SK. Role of energy transition in easing energy security risk and decreasing CO_2 emissions: disaggregated level evidence from the USA by quantile-based models. J Environ Manage 2024;359:120971.
[27] Kartal MT, Ayhan F, Ulussever T. Impact of environmental policy stringency on sectoral GHG emissions: evidence from Finland and Sweden by nonlinear quantile-based methods. Int J Sustain Dev World Ecol 2024;31(7):848–60.
[28] Awosusi AA, Adebayo TS, Kirikkaleli D, Altuntaş M. Role of technological innovation and globalization in BRICS economies: policy towards environmental sustainability. Int J Sustain Dev World Ecol 2022;29 (7):593–610.
[29] Kraft J, Kraft A. On the relationship between energy and GNP. J Energy Devel 1978;3(2):401–3.
[30] Ben Cheikh N, Ben Zaied Y, Chevallier J. On the nonlinear relationship between energy use and CO_2 emissions within an EKC framework: evidence from panel smooth transition regression in the MENA region. Res Int Bus Finance 2021;55:101331.
[31] Ali MU, Gong Z, Ali MU, Wu X, Yao C. Fossil energy consumption, economic development, inward FDI impact on CO_2 emissions in Pakistan: testing EKC hypothesis through ARDL model. Int J Finance Econ 2021;26(3):3210–21.
[32] Islam MS, Rahaman SH. The asymmetric effect of ICT on CO_2 emissions in the context of an EKC framework in GCC countries: the role of energy consumption, energy intensity, trade, and financial development. Environ Sci Pollut Res Int 2023;30(31):77729–41.
[33] Kartal MT, Kirikkaleli D, Pata UK. Role of environmental policy stringency on sectoral CO_2 emissions in EU-5 countries: disaggregated level evidence by novel quantile-based approaches. Energy Environ 2026;37(1):336–61.
[34] Porter ME, Linde CVD. Toward a new conception of the environment-competitiveness relationship. J Econ Perspect 1995;9(4):97–118.
[35] Dechezleprêtre A, Sato M. The impacts of environmental regulations on competitiveness. Rev Environ Econ Policy 2017;11(2):183–206.
[36] Wolde-Rufael Y, Mulat-Weldemeskel E. Do environmental taxes and environmental stringency policies reduce CO_2 emissions? Evidence from 7 emerging economies. Environ Sci Pollut Res Int 2021;28(18):22392–408.
[37] Afshan S, Öztürk İ, Yaqoob T. Facilitating renewable energy transition, ecological innovations and stringent environmental policies to improve ecological sustainability: evidence from MM-QR method. Renew Energy 2022;196:151–60.
[38] Wang Z, Yen-Ku K, Li Z, An NB, Abdul-Samad Z. The transition of renewable energy and ecological sustainability through environmental policy stringency: estimations from advance panel estimators. Renew Energy 2022;188:70–80.
[39] Bashir MF, Rao A, Sharif A, Ghost S, Pan Y. How do fiscal policies, energy consumption and environmental stringency impact energy transition in the G7 economies: policy implications for the COP28. J Clean Prod 2024;434:140367.
[40] Gibba A, Khan MK, Jallow MA, Sanneh T, Bojang B, Touray M. Interrelationship among institutional quality, energy consumption and environmental degradation in Australia: a dynamic autoregressive distributed lag approach. Int J Environ Sci Technol 2025;22:10345–64.
[41] Kartal MT, Mukhtarov S, Kirikkaleli D. Achieving environmental quality through stringent environmental policies: comparative evidence from G7 countries by multiple environmental indicators. Geosci Frontiers 2025;16 (1):101956.
[42] Bashir MF, Pan Y, Shahbaz M, Ghosh S. How energy transition and environmental innovation ensure environmental sustainability? Contextual evidence from Top-10 manufacturing countries. Renew Energy 2023;204:697–709.

[43] Bashir MF, Shahbaz M, Malik MN, Ma B, Wang J. Energy transition, natural resource consumption and environmental degradation: the role of geopolitical risk in sustainable development. Resour Policy 2023;85:103985.
[44] Ahmad M, Ahmed Z, Riaz M, Yang X. Modeling the linkage between climate-tech, energy transition, and CO_2 emissions: do environmental regulations matter? Gondwana Res 2024;127:131–43.
[45] Wang Q, Guo J, Li R, Xue-ting JX. Economic growth and carbon emission in the Organization for Economic Cooperation and Development countries: the effects of oil, gas, and renewable energy. Energy Environ 2024;35(4):2107–30.
[46] Dong Y, Zhang Y, Liu S. The impacts and instruments of energy transition regulations on environmental pollution. Environ Impact Assess Rev 2024;105:107448.
[47] Wang X, Sun X, Ahmad M, Chen J. Energy transition, ecological governance, globalization, and environmental sustainability: insights from the top ten emitting countries. Energy 2024;292:130551.
[48] Wang Q, Li Y, Li R. Ecological footprints, carbon emissions, and energy transitions: the impact of artificial intelligence (AI). Hum Soc Sci Commun 2024;11(1):1043.
[49] Shafik N, Bandyopadhyay S. Economic growth and environmental quality: time-series and cross-country evidence. Report. Washington, DC: World Bank Publications; 1992.
[50] Liu X, Bae J. Urbanization and industrialization impact of CO_2 emissions in China. J Clean Prod 2018;172:178–86.
[51] Ahmad M, Ahmed Z, Majeed A, Huang B. An environmental impact assessment of economic complexity and energy consumption: does institutional quality make a difference? Environ Impact Assess Rev 2021;89:106603.
[52] Ahmad M, Jiang P, Murshed M, Shehzad K, Akram R, Cui L, et al. Modelling the dynamic linkages between eco-innovation, urbanization, economic growth and ecological footprints for G7 countries: does financial globalization matter? Sustain Cities Soc 2021;70:102881.
[53] Chen F, Wang L, Gu Q, Wang M, Ding X. Nexus between natural resources, financial development, green innovation and environmental sustainability in China: fresh insight from novel quantile ARDL. Resour Policy 2022;79:102955.
[54] Gupta M, Saini S, Sahoo M. Determinants of ecological footprint and PM2.5: role of urbanization, natural resources and technological innovation. Environ Chall 2022;7:100467.
[55] Peng G, Meng F, Ahmed Z, Ahmad M, Kurbonov K. Economic growth, technology, and CO_2 emissions in BRICS: investigating the non-linear impacts of economic complexity. Environ Sci Pollut Res Int 2022;29(45):68051–62.
[56] Xue C, Shahbaz M, Ahmed Z, Ahmad M, Sinha A. Clean energy consumption, economic growth, and environmental sustainability: what is the role of economic policy uncertainty? Renew Energy 2022;184:899–907.
[57] Qayyum M, Yu Y, Nizamani MM, Raza S, Ali M, Li S. Financial instability and CO_2 emissions in India: evidence from ARDL bound testing approach. Energy Environ 2023;34(4):808–29.
[58] Magazzino C. Ecological footprint, electricity consumption, and economic growth in China: geopolitical risk and natural resources governance. Empir Econ 2024;66(1):1–25.
[59] Yasin I, Amin S, Mehmood W. Financial development's role in reducing the ecological footprint of energy consumption in BRICS. Sustain Dev 2025;33(3):4174–90.
[60] Data of GDP [database]. Washington, DC: World Bank Group; 2024.
[61] Broock WA, Scheinkman JA, Dechert WD, Lebaron B. A test for independence based on the correlation dimension. Econom Rev 1996;15(3):197–235.
[62] Hainmueller J, Hazlett C. Kernel regularized least squares: reducing misspecification bias with a flexible and interpretable machine learning approach. Polit Anal 2014;22(2):143–68.
[63] Sinha A, Ghosh V, Hussain N, Nguyen DK, Das N. Green financing of renewable energy generation: capturing the role of exogenous moderation for ensuring sustainable development. Energy Econ 2023;126:107021.