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RESEARCH ARTICLE OPEN ACCESS

How Can SDG-13 Be Achieved by Energy, Environment, and Economy-Related Policies? Evidence From Five Leading Emerging Countries

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Received: 6 August 2024 | **Revised:** 17 January 2025 | **Accepted:** 3 February 2025

Keywords: economic policies | emerging countries | energy policies | environmental policies | environmental Progress | KRLS approach

ABSTRACT

The adverse effects of climate change on humanity have been escalating due to environmental degradation. Consequently, nations have been compelled to implement measures to address climate-related challenges. Within this framework, traditional and recently acknowledged factors play a pivotal role in achieving SDGs, particularly SDG-13. This study empirically examines the influence of newly recognized factors, such as the energy transition index (ETI) and environmental policy stringency (EPS), alongside traditional factors like gross domestic product (GDP), renewable energy use (REU), and foreign direct investments (FDI), on the environment, measured through ecological footprint and load capacity factor. Focusing on leading emerging economies—excluding Indonesia and Mexico due to data limitations—the study utilizes data from 2000 to 2020 and applies the kernel-based regularized least squares (KRLS) approach under the marginal effect framework to explore this nexus. The findings indicate that (i) GDP and FDI do not exhibit environmentally friendly characteristics across the examined countries; (ii) REU contributes to environmental preservation only in Brazil; (iii) ETI and EPS do not significantly enhance environmental quality in any of the countries studied; (iv) the KRLS approach demonstrates high predictive accuracy, achieving a 99.6% success rate across various models. Overall, the research highlights the differential marginal effects of these factors on the environment, which vary by factor, percentile, and country. Based on the empirical evidence, the study discusses policy implications for the five leading emerging economies to effectively pursue SDG-13 by leveraging the identified factors.

1 | Introduction

Environmental degradation ranks among the most urgent and intricate challenges confronting the world today. The extensive fossil fuel reliance since the Industrial Revolution, coupled with intensifying economic activities, industrial pollution, and unsustainable agricultural practices, is a principal contributor to this degradation (Steffen et al. 2015). The persistent rise in emissions, deforestation, sea level rise, declining air quality, water pollution, and biodiversity loss has destabilized ecosystems

Abbreviations: AME, average marginal effect; BDS, Broock, Scheinkman, Dechert, and LeBaron; BRA, Brazil; CHN, China; EFP, ecological footprint; EKC, environmental Kuznets curve; EPS, environmental policy stringency; ETI, energy transition index; FDI, foreign direct investments; GDP, gross domestic product; IND, India; LCF, load capacity factor; PME, pointwise marginal effect; REU, renewable energy use; RUS, Russia; TUR, Türkiye.

and presents significant threats to the planet's sustainability (Rockström et al. 2009; UNEP 2019).

EFP serves as a crucial indicator for gauging the magnitude of this threat, quantifying the extent to which human activities surpass the Earth's biological capacity (Wackernagel and Rees 1996). EFP measures the natural resources required to produce the goods consumed by a population and to assimilate the resulting waste, considering current technological capabilities (Hoekstra 2009). As a significant indicator, EFP effectively captures the diverse environmental effects of human activities. Therefore, it is essential to identify the factors influencing EFP, particularly in leading emerging economies undergoing development. The trend of EFP progression is illustrated in Figure 1.

As illustrated in Figure 1, there is a discernible upward trend in EFP of the five leading developing countries, with a particularly pronounced increase in China and India since 2000. This trend underscores the growing consumption of natural resources driven by factors such as economic and population growth. In contrast, other countries exhibit more moderate increases in EFP, reflecting a balance between resource usage and environmental effects. The varying rates of EFP increase among these nations may highlight disparities in their environmental management frameworks.

SDGs aim to harmonize economic growth with environmental sustainability through an integrated approach (United Nations 2015). Specifically, SDG-13 calls for action to combat climate change and promote adaptive strategies, while SDG-7 focuses on ensuring access to sustainable clean energy. Access to clean energy supports sustainable practices across various sectors, facilitating a transition to a low-carbon economy and promoting energy efficiency and innovation (IEA 2021). Achieving universal access to clean energy is crucial for aligning national development strategies with climate action objectives. In this regard, the attainment of SDG-7 is vital for the realization of SDG-13, as transitioning to renewable energy sources significantly curtails emissions, thereby mitigating climate change.

SDGs target both economic growth and environmental sustainability and provide an integrated approach to these challenges (United Nations 2015). Among all, SDG-13 calls for action to mitigate climate change effects. In addition, SDG-7 aims to ensure access to affordable, reliable, and sustainable energy. Access to clean energy fosters sustainable practices across sectors, enabling a low-carbon economy while promoting energy efficiency and innovation (IEA 2021). By ensuring universal access to clean energy, countries can align their development strategies with their climate action goals. In this context, the achievement of SDG-7 can play a crucial role in ensuring SDG-13, as the transition to renewable sources significantly reduces emissions and thus mitigates climate change.

To achieve these goals, the integration and effective implementation of energy, environmental, and economic policies are imperative. Numerous global and country-specific initiatives have been undertaken to reduce environmental degradation, with the Paris Agreement being one of the most significant. This international climate pact, legally binding and endorsed by 196 parties on 12th December 2015 at the UN climate change conference, aims to limit the global average temperature increase to well below 2°C above pre-industrial levels, striving to cap it at 1.5°C. IPCC (2014) warns that surpassing the 1.5°C threshold could trigger more severe climate change consequences, including more frequent and intense droughts, heatwaves, and precipitation events (UNFCCC 2015).

Energy efficiency, the adoption of renewable energy sources, and the implementation of sustainable transportation policies are crucial for reducing fossil fuel reliance and promoting clean production and technologies, thereby mitigating environmental degradation (IRENA 2021). However, current policies and practices remain insufficient to halt climate change and environmental deterioration. In 2023, GHG concentrations reached unprecedented levels, ensuring a continued rise in global temperatures (WMO 2023). CO_2 accumulation in the atmosphere has surged at an unprecedented rate, increasing by nearly 10% over a few decades, with global average atmospheric CO_2 concentrations reaching a record high of 420.0 ± 0.1 ppm in 2023. Compared with pre-industrial levels (before 1750), atmospheric CO_2 concentrations have risen by 151% (WMO 2023; ICOS 2024). This significant increase

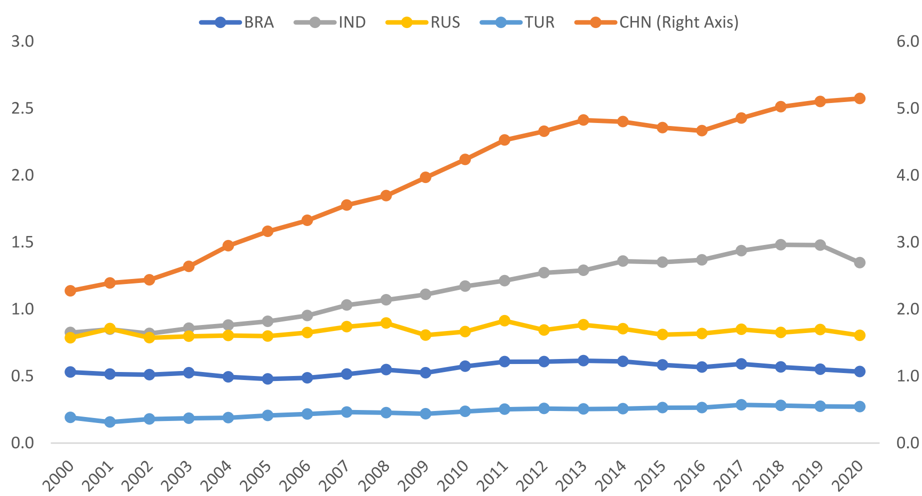

FIGURE 1 | Environmental progress provided by EFP in Leading Emerging Countries. *Source:* Global Footprint Network (GFN 2024). The unit isonee billion hectares.

underscores the urgent need to reassess the environmental effects of economic growth and development policies.

Research on environmental sustainability indicates that traditional economic indicators, such as GDP, FDI, financial development, international trade, population, and energy use, often have complex and detrimental environmental effects (Stern 2004; Sadorsky 2009). Economic growth models dependent on fossil fuels exacerbate climate change by increasing emissions (IPCC 2014). Conversely, the transition to renewable energy sources and enhanced energy efficiency presents substantial opportunities for emission reduction (Shafiei and Salim 2014). Renewable energy is a pivotal factor in promoting environmental sustainability, energy security, and sustainable economic development (United Nations 2015; IEA 2021). Globally, renewable energy is essential for achieving a net-zero carbon-energy system. Therefore, prompt and substantial investment in renewable energy is imperative to mitigate the alarming rise in global temperatures (Hasanov et al. 2020).

Recent studies have introduced indicators such as ETI (Kartal, Shahbaz, et al. 2024; Kartal, Taşkın, et al. 2024; Tiwari, Mohammed, et al. 2024) and EPS (Sezgin et al. 2021; Udeagha and Ngepah 2023; Dmytrenko et al. 2024; Kartal, Kirikkaleli, and Pata 2024; Sohag et al. 2024) to assess countries' progress toward sustainable energy systems and the efficacy of environmental policies. However, the practical effectiveness of these policies in reducing environmental degradation remains a subject of debate (Lamb and Minx 2020). New research is necessary to explore the environmental effects of these indicators, particularly how ETI and EPS influence environmental degradation. Figure 2 illustrates the ETI trend for five leading emerging countries, highlighting a critical subset of nations in this context.

Figure 2 demonstrates a general upward trend in ETI from 2000 to 2020, indicating that these countries have made progress in increasing REU and reducing their reliance on fossil fuels. Among them, China and India have shown the most consistent rise in energy transition, while Brazil and South Africa display more fluctuating patterns. These variations reflect the differences in energy policies and investments in sustainable energy across these nations. Advancing energy transition not only yields environmental benefits but also enhances energy security.

Policies that promote sustainable resource utilization, reduce emissions, and encourage eco-friendly behaviors play a crucial role in mitigating environmental effects. Effective environmental policies are integral to managing the EFP. Regulatory measures (e.g., environmental taxes and emission trading) have been implemented to combat environmental degradation (Chu and Tran 2022; Mukhtarov 2022). Stringent environmental policies typically include targets for emission reductions, carbon pricing mechanisms, and strategies to improve energy efficiency. The EPS indicator, developed by the OECD, aggregates various policy data to measure the relative strictness of environmental policies across countries and over time (OECD 2016). These policies incentivize industries to adopt cleaner technologies, contributing to emission reductions. The effectiveness of such policies is closely linked to the enforcement levels mandated by regulations (Mihai et al. 2023). Given the increasing global focus on environmental measures, particularly in leading emerging countries, it is crucial to analyze the effect of environmental policies on mitigating environmental degradation. Figure 3 below illustrates the progression of EPS in the five leading emerging countries.

As observed in Figure 3, EPS has generally increased, although the rate of increase varies across countries. China and India have exhibited a continuous rise in EPS, while Brazil and South Africa have maintained relatively stable and fluctuating patterns. Notably, Russia has shown a significant increase in EPS, particularly after 2010. These differences highlight the varying approaches to environmental regulation among these nations.

The implementation of stringent energy policies and the transition to sustainable energy systems are crucial to mitigating environmental degradation. Therefore, examining the effects of ETI and EPS on the environment is essential. A review of the existing literature reveals an insufficiency of studies that analyze the combined effect of ETI and EPS on environmental pollution. To date, only Tiwari, Mohammed, et al. (2024) have investigated the joint effect of these indicators on environmental degradation. This gap in the literature, particularly regarding their simultaneous effects on EFP in

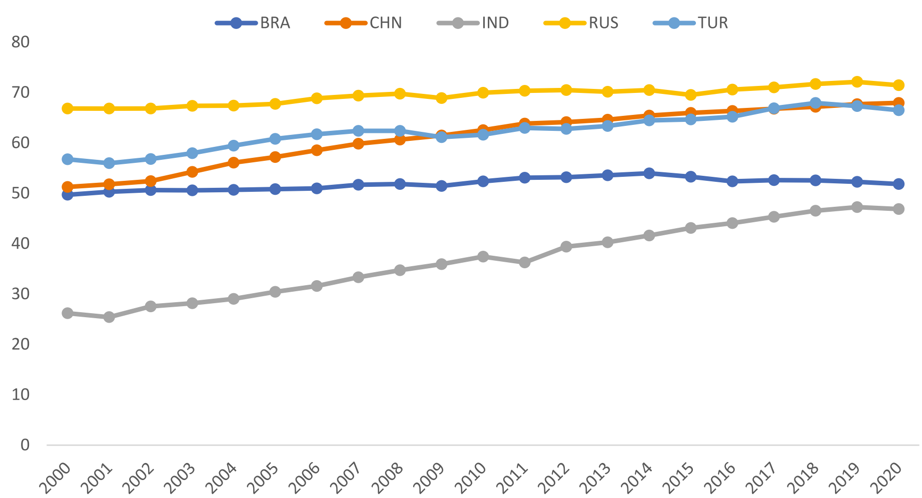

FIGURE 2 | Progress of energy transition in leading emerging countries. *Source:* UNCTAD (2024). The unit is the index.

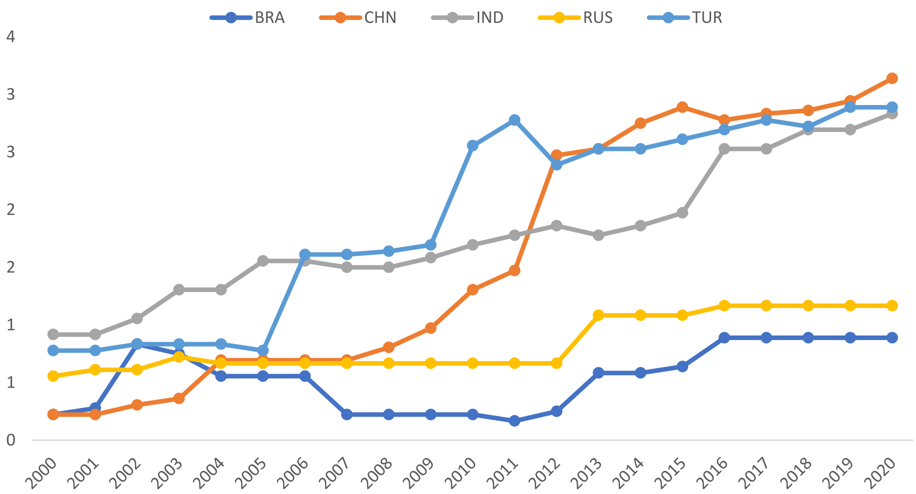

FIGURE 3 | Progress of EPS in leading emerging countries. *Source:* OECD (2024). The unit is the index.

leading emerging countries, underscores the need for further research. Accordingly, this study addresses this gap by uncovering critical research questions: (i) How does EPS mitigate EFP? (ii) What role does ETI play in reducing EFP? (iii) How do GDP, FDI, and REU influence EFP? (iv) How do these variables' effects vary across countries and percentiles? To answer these questions, the study employs the KRLS approach to analyze the marginal effects of EPS, ETI, GDP, REU, and FDI on EFP, using annual data from 2000 to 2022. The focus is on five leading emerging countries, which collectively contribute 40.2% of global greenhouse gas emissions (EDGAR 2023). These countries' performances in achieving SDGs are crucial for global environmental sustainability, making them central to this analysis.

This study contributes to the existing knowledge. First, it is one of the few studies to simultaneously examine the effects of EPS and ETI on EFP, with a focus on five leading emerging countries. Secondly, it utilizes ETI as a comprehensive metric for energy transition, encompassing various elements such as energy accessibility, sustainability, and renewable energy components, rather than merely emphasizing the renewable energy share in the energy mix. Thirdly, in addition to EFP, the study uses the LCF as an environmental proxy, offering a more comprehensive assessment of environmental quality (Siche et al. 2010; Altıntaş et al. 2023). Finally, by applying the KRLS approach, the study captures the nonlinear nexus between variables and reveals how marginal effects vary across percentiles (Hainmueller and Hazlett 2014). The findings indicate that the current policy frameworks in these countries are inadequate for achieving SDG-13, highlighting the need for more comprehensive and targeted strategies. Based on the empirical results, the study proposes various policy recommendations for the examined countries and others with similar characteristics to advance towards the SDGs.

The structure of the study is as follows: Section 2 presents the theoretical framework and a review of empirical literature. Section 3 outlines the methodology. Section 4 discusses the empirical results, along with policy implications. Finally, Section 5 concludes.

2 | Theoretical Underpinning and Literature Review

2.1 | Theoretical Background

The contemporary environmental economics literature builds upon the foundational work of Kraft and Kraft (1978) and Grossman and Krueger (1991). These seminal studies introduce the energy-led growth hypothesis and the EKC hypothesis, respectively. The energy-led growth hypothesis posits a strong nexus between energy consumption and economic growth, suggesting that this nexus may be unidirectional or bidirectional. In contrast, the EKC hypothesis proposes a mixed nexus between income and environmental quality, predicated on scale, structural, and technological effects. According to the EKC hypothesis, environmental degradation initially increases with rising per capita income but eventually declines after reaching a specific income threshold (Grossman and Krueger 1991).

Following the pioneering contributions of Kraft and Kraft (1978) and Grossman and Krueger (1991), subsequent studies have explored the effect of income and various energy types on the environment, using indicators such as CO_2 emissions and EFP. However, recent advancements in the literature have introduced LCF as a novel environmental indicator, as proposed by Pata and Kartal (2023). Unlike traditional indicators, LCF accounts for both the supply (biocapacity) and demand (EFP) aspects of natural resources, providing a more holistic measure of environmental sustainability. Consequently, recent research has increasingly employed LCF as a comprehensive environmental metric.

Additionally, the pollution halo hypothesis (PLH) and the pollution haven hypothesis (PHH) offer theoretical frameworks for understanding the environmental effect of FDI. The PLH suggests that FDI can reduce environmental degradation through investments in eco-friendly technologies, while the PHH argues that FDI may exacerbate environmental degradation by relocating pollution-intensive industries to countries with lax environmental regulations (Abbasi et al. 2023; Blanco et al. 2013).

While these theories provide a robust foundation for empirical investigations, they have been critiqued for their limitations. To address these gaps, it is essential to expand the theoretical frameworks by incorporating additional factors. This study, therefore, analyzes ETI, EPS, and FDI to better understand their roles in promoting clean technologies and sustainable practices. By integrating these factors, the study aims to provide a more comprehensive understanding of environmental progress and its determinants.

2.2 | Empirical Literature

The empirical literature reveals a growing interest in examining the roles of ETI and EPS, alongside traditional factors, in influencing environmental progress. This section reviews the empirical studies concerning each critical factor (i.e., ETI, EPS, GDP, REU, and FDI) in sequence.

2.2.1 | ETI and Environment Nexus

Recent energy crises have spurred an increase in empirical studies investigating the nexus between ETI and environmental progress. Researchers have employed various proxies to measure environmental progress, including EFP (Khan et al. 2022), CO_2 emissions (Fatima, Xuhua, Alnafisah, Zeast, and Akhtar 2024; Kartal, Shahbaz, et al. 2024), and LCF (Tiwari, Mentel, et al. 2024; Uche et al. 2024). Notably, while country-specific studies remain scarce (e.g., Kartal, Shahbaz, et al. 2024; Kartal, Taşkın, et al. 2024), most research focuses on groups such as OECD (e.g., Sheraz et al. 2024), G-7 (e.g., Fatima, Xuhua, Alnafisah, Zeast, and Akhtar 2024), and BRICS (e.g., Uche et al. 2024).

Studies generally recognize the negative effect of ETI on environmental degradation. For example, Khan et al. (2022) provide evidence of ETI's contractionary effect on EFP in OECD countries. Fatima, Xuhua, Alnafisah, Zeast, and Akhtar (2024) find that ETI and EPS, moderated by technological innovation, reduce CO_2 emissions in G-7 countries by using CCR, DOLS, FMOLS, and MMQR. Contrarily, Tiwari, Mohammed, et al. (2024) argue that ETI increases CO_2 emissions, whereas EPS decreases them by using the CS-ARDL approach. Research by Kartal, Shahbaz, et al. (2024) with the WLMC approach suggests varying effects of ETI across Nordic countries, with Finland and Norway experiencing decreases and Sweden experiencing increases. Moreover, Kartal, Taşkın, et al. (2024) show that the effect of ETI on environmental degradation may be neutral in some sectors (industry and power) and decreasing in others (building and transport) at low quantiles with quantile-based approaches for the USA.

In two recent studies presenting the findings of ETI on LCF, Tiwari, Mentel, et al. (2024) use the CS-ARDL approach to highlight the effect on five countries, while Uche et al. (2024), unlike other studies, focus on BRICS countries' transition to low-carbon energy use as green transition on LCF, and prove a similar finding for BRICS countries by using AMG, CS-ARDL, and MMQR approaches. On the other hand, Sheraz et al. (2024) affirm ETI's role in reducing GHG emissions across 37 OECD countries.

Panel A of Table 1 summarizes the findings of empirical studies that examine the effect of ETI on the environment. Overall, the literature indicates mixed effects of ETI on environmental progress, underscoring the need for further research.

2.2.2 | EPS and Environment Nexus

Studies on EPS, which examine the effect of EPS on the environment, have typically focused on similar country groups (e.g., OECD and BRICS) and employed similar approaches (e.g., CCR, DOLS, FMOLS, and CS-ARDL). These studies use various environmental proxies and yield differing results. For instance, Sadik-Zada and Ferrari (2020) conduct a PMG analysis for 26 OECD countries and find that EPS does not influence CO_2 emissions in the short run, whereas EPS enhances CO_2 emissions in the long run, while Tiwari, Mentel, et al. (2024) reveal no significant nexus between EPS and LCF with the CS-ARDL approach for 24 OECD countries.

Contrasting findings include Wang et al. (2022), who demonstrate that EPS and REU reduce CO_2 emissions in BRICS countries. Similarly, Fatima, Xuhua, Alnafisah, and Akhtar (2024) highlight the combined effectiveness of ETI and EPS in GHG reduction for OECD countries.

Sohag et al. (2024) prove that EPS can effectively reduce EFP by using innovation channels and renewable energy for OECD countries. On the other hand, Yıldırım et al. (2024) provide evidence that EPS and REU increase LCF, but FDI decreases LCF by using the CS-ARDL approach for BRICS countries. Unlike these studies, Li et al. (2022) find evidence that EPS with solar energy consumption reduces CO_2 emissions in OECD countries.

Panel B of Table 1 summarizes the findings of empirical studies that examine the effect of EPS on the environment. Despite varied results, the literature shows no consensus on EPS's environmental effect, necessitating additional research.

2.2.3 | GDP and Environment Nexus

The effect of GDP on the environment has been widely examined, particularly within the context of the EKC hypothesis. Many studies also consider REU (e.g., Mirziyoyeva and Salahodjaev 2022; Dam et al. 2023) and FDI (e.g., Sreenu 2022; Gao et al. 2023) as explanatory variables along with GDP.

Generally, findings suggest that GDP growth increases environmental degradation (e.g., Sreenu 2022; Li et al. 2023; Yasin et al. 2025). Hasanov et al. (2021) also conclude that GDP and REU increase CO_2 emissions by using the CS-ARDL approach for BRICS countries. Similarly, Sreenu (2022) shows that GDP and FDI increase CO_2 emissions in India by performing the NARDL approach.

However, some studies, like Mirziyoyeva and Salahodjaev (2022), find that GDP and REU decrease CO_2 emissions by using panel fixed effects and GMM approaches for ten countries with the highest CO_2 emissions.

TABLE 1 | Empirical literature summary.

Panel	Authors	Sample countries	Time period	Econometric approach	Empirical result
Panel A: ETI-environment	Khan et al. (2022)	OECD	1990–2015	Westerlund Cointegration	ETI ↓ EFP
	Fatima, Xuhua, Alnafisah, Zeast, and Akhtar (2024)	G7	1990–2020	DOLS, FMOLS, CCR, MMQR	ETI ↓ CO_2
	Kartal, Shahbaz, et al. (2024)	Nordic	2000/1–2021/12	WLMC	ETI ↑↓ CO_2
	Kartal, Taşkın, et al. (2024)	USA	2001/Q1-2022/Q4	QQR, QQ, GCQ	ETI ↑↓ CO_2
	Sheraz et al. (2024)	37 OECD	2000–2021	DOLS, FMOLS, DH	ETI ↓ GHG
	Tiwari, Mohammed, et al. (2024)	Selected 5	1997–2020	CS-ARDL	ETI ↑ CO_2
	Tiwari, Mentel, et al. (2024)	BRIC +1	1993–2020	CS-ARDL	ETI ↑ LCF
	Uche et al. (2024)	BRICS	1981–2021	MMQR, AMG, CS-ARDL	ETI ↑ LCF
Panel B: EPS-environment	Sadik-Zada and Ferrari (2020)	26 OECD	1995–2011	PMG	EPS ↑ CO_2
	Li et al. (2022)	15 OECD	2001–2018	CS-ARDL	EPS ↓ CO_2
	Wang et al. (2022)	BRICS	1990–2019	CS-ARDL	EPS ↓ CO_2
	Fatima, Xuhua, Alnafisah, Zeast, and Akhtar (2024)	G7	1990–2020	DOLS, FMOLS, CCR, MMQR	EPS ↓ CO_2
	Sohag et al. (2024)	24 OECD	1990–2018	CS-ARDL	EPS ↓ CO_2
	Tiwari, Mohammed, et al. (2024)	Selected 5	1997–2020	CS-ARDL	EPS ↓ CO_2
	Tiwari, Mentel, et al. (2024)	BRIC +1	1993–2020	CS-ARDL	EPS ≠ LCF
	Yıldırım et al. (2024)	BRICS	1992–2020	CS-ARDL	EPS ↑ LCF
Panel C: GDP-environment	Hasanov et al. (2021)	BRICS	1990–2017	CS-ARDL	GDP ↑ CO_2
	Mirziyoyeva and Salahodjaev (2022)	Top CO_2 Emitting	2000–2015	FE, GMM	GDP ↓ CO_2
	Sreenu (2022)	India	1990–2020	ARDL, NARDL	GDP^+ ↑ CO_2
	Dam et al. (2023)	22 OECD	1999–2018	PMG, ARDL	GDP ↓ LCF
	Gao et al. (2023)	China	2001–2019	RBM-ML	GDP ↑ CEE
	Javed et al. (2023)	Italy	1994–2019	DARDL	GDP ↑ EFP
	Li et al. (2023)	BRICS	1990–2019	CCEMG, AMG	GDP ↑ CO_2
	Xu et al. (2023)	E7	2000–2021	MMQR	GDP ↑ CO_2
	Shah and Ximei (2024)	BRICS-T	1990–2022	FMOLS, DOLS	GDP ↑ EFP

(Continues)

TABLE 1 | (Continued)

Panel	Authors	Sample countries	Time period	Econometric approach	Empirical result
Panel D: REU-environment	Hasanov et al. (2021)	BRICS	1990–2017	CS-ARDL	REU ↑ CO_2
	Abbasi et al. (2022)	Türkiye	1990–2018	NARDL, FMOLS, DOLS, CCR	REU^- ↓ CO_2
	Akinsola et al. (2022)	Brazil	1983–2017	ARDL, DOLS	REU ↓ EFP
	Khan et al. (2022)	OECD	1990–2015	Westerlund Cointegration	REU ↓ EFP
	Li et al. (2022)	15 OECD	2001–2018	CS-ARDL	SEC ↓ CO_2
	Wang et al. (2022)	BRICS	1990–2019	CS-ARDL	REU ↓ CO_2
	Dam et al. (2023)	22 OECD	1999–2018	PMG, ARDL	REU ↑ LCF
	Li et al. (2023)	BRICS	1990–2019	CCEMG, AMG	REU ↓ CO_2
	Javed et al. (2023)	Italy	1994–2019	DARDL	REU ↓ EFP
	Samour et al. (2023)	USA	1983–2020	ARDL	REU ↑ LCF
	Wang et al. (2023)	Selected 24	2001–2020	Panel FMOLS	REU & NEC ↓ CO_2
	Shah and Ximei (2024)	BRICS-T	1990–2022	FMOLS, DOLS	REU ↓ EFP
	Sohag et al. (2024)	24 OECD	1990–2018	CS-ARDL	REU ↓ CO_2
	Yıldırım et al. (2024)	BRICS	1992–2020	CS-ARDL	REU ↑ LCF
Panel E: FDI-environment	Blanco et al. (2013)	18 Latin American	1980–2007	GC	FDI→CO_2
	Nasir et al. (2019)	ASEAN-5	1982–2014	FMOLS, DOLS	FDI ↑ CO_2
	Abbasi et al. (2022)	Türkiye	1990–2018	NARDL, FMOLS, DOLS, CCR	FDI ↑ CO_2
	Li et al. (2022)	China	1990–2017	FMOLS, DOLS, CCR	FDI ↑ EFP
	Sreenu (2022)	India	1990–2020	ARDL, NARDL	FDI ↑ CO_2
	Apergis et al. (2023)	11 OECD & BRICS	1993–2012	GMM	FDI ↓ CO_2
	Gao et al. (2023)	China	2001–2019	RBM-ML	FDI ↑ CEE
	Xu et al. (2023)	E7	2000–2021	MMQR	FDI ↓ CO_2
	Yıldırım et al. (2024)	BRICS	1992–2020	CS-ARDL	FDI ↓ LCF

Abbreviations: ↑, increasing effect; ↓, decreasing effect; ↔, bidirectional causality; →, unidirectional causality; ≠, no causality; AMG, augmented mean group; ARDL, autoregressive distributed lag; CEE, carbon emission efficiency; CCEMG, common correlated effects mean group; CCR, canonical cointegration regression; CS-ARDL, cross-sectional ARDL; DARDL, dynamic ARDL; DOLS, dynamic ordinary least squares; FMOLS, fully modified ordinary least squares; GC, Granger causality; GCQ, granger causality in quantiles; GMM, generalized method of moments; DH, Dumitrescu and Hurlin; MMQR, method of moments quantile regression; NARDL, nonlinear ARDL; NEC, nuclear energy consumption; PMG, pooled mean group; QQR, quantile on quantile regression; QR, quantile regression; SEC, solar energy consumption; WLMC, wavelet local multiple correlation.

Dam et al. (2023) present that GDP (REU) decreases (increases) LCF by using PMG and ARDL approaches for OECD countries. On the other hand, Gao et al. (2023) draw attention to the difference in the short (decreasing) and long (increasing) term effects of GDP and FDI on CO_2 emission efficiency. Li et al. (2023) determine that GDP growth triggers environmental degradation by increasing CO_2 emissions, but REU and EPS have a reducing effect on CO_2 emissions in BRICS countries by using CCEMG and AMG approaches. Also, Ahakwa et al. (2023) draw attention to an N-shaped nexus between GDP and environmental degradation in Ghana by performing the QQR approach, which supports the EKC hypothesis.

Panel C of Table 1 summarizes the findings of empirical studies that examine the effect of GDP on the environment. Despite varied results, the literature shows no consensus on EPS's environmental effect, necessitating additional research.

2.2.4 | REU and Environment Nexus

Recent studies have increasingly focused on the nexus between REU and environmental progress, using both aggregated and disaggregated level REU. Commonly used proxies include CO_2 emissions (Wang et al. 2023), EFP (Akinsola et al. 2022; Wang, Li, and Li 2024; Wang, Zhang, et al. 2024), and LCF (Samour et al. 2023).

By using ARDL and DOLS approaches for Brazil, Akinsola et al. (2022) show that REU reduces EFP, while Usman and Radulescu (2022) confirm the role of REU and nuclear energy in reducing EFP. Other studies, like Javed et al. (2023) and Samour et al. (2023), validate REU's positive effect on reducing environmental degradation. Javed et al. (2023) claim that REU (GDP) decreases (increases) EFP for Italy, while Samour et al. (2023) reveal that REU supports LCF by using the ARDL approach for the USA. Likewise, Wang et al. (2023) emphasize that REU and nuclear energy use reduce environmental pollution by using the panel FMOLS approach for 24 countries. Moreover, Shah and Ximei (2024) prove the differential effects of REU and GDP growth on EFP by performing FMOLS and DOLS approaches in BRICS-T countries.

However, some findings, such as those by Hasanov et al. (2021) for BRICS, indicate REU's inefficiency in reducing CO_2 emissions, highlighting methodological and contextual differences, country groups, and periods across studies.

Panel D of Table 1 summarizes the findings of empirical studies that examine the effect of REU on the environment. Overall, while REU is generally seen as effective in reducing environmental degradation, the literature remains inconclusive, warranting further exploration.

2.2.5 | FDI and Environment Nexus

Empirical studies on FDI's environmental effect present diverse effects. Blanco et al. (2013) and Nasir et al. (2019) confirm FDI's role in increasing CO_2 emissions in Latin America and ASEAN countries, respectively. Similarly, Li et al. (2022) find that FDI exacerbates EFP in China. Specifically, Blanco et al. (2013) confirm a causality from FDI to CO_2 by implementing a causality study for 18 Latin American countries. Similarly, Nasir et al. (2019) prove a similar result for ASEAN countries by performing FMOLS, DOLS, and CCR approaches. Likewise, Li et al. (2022) present the increasing effect of FDI on EFP in China by applying FMOLS, DOLS, and CCR approaches.

Conversely, Apergis et al. (2023) and Xu et al. (2023) provide evidence of FDI's role in reducing CO_2 emissions in OECD, BRICS, and E7 countries. Yıldırım et al. (2024) also highlight FDI's contractionary effect on LCF in BRICS nations. Precisely, Apergis et al. (2023) determine that FDI has a CO_2 emission-reducing effect in OECD and BRICS countries by performing the GMM approach, while Xu et al. (2023) prove that FDI decreases CO_2 emissions in E7 countries by using the MMQR approach. Likewise, Yıldırım et al. (2024) reveal the contractionary effect of FDI on LCF in BRICS countries by performing the CS-ARDL approach.

Panel E of Table 1 summarizes the findings of empirical studies that examine the effect of FDI on the environment. Given these mixed findings, further analysis is essential to clarify FDI's environmental effect.

2.3 | Evaluation of the Empirical Literature

This section summarizes the key findings from studies examining the nexus between ETI, EPS, GDP, REU, FDI, and environmental progress, as presented in Table 1. The literature reveals a lack of consensus on the effects of these factors, emphasizing the need for continued research to inform policy-making and environmental strategies.

Given the general trends in applied research, it is notable that recent periods have witnessed a significant increase in studies examining the effects of ETI and EPS on the environment. Alongside ETI and EPS, other variables such as GDP, REU, and FDI are frequently incorporated into these analyses. A review of the literature summarized in Table 1 reveals a diversity of findings. Some studies indicate that ETI mitigates environmental degradation (e.g., Khan et al. 2022; Fatima, Xuhua, Alnafisah, Zeast, and Akhtar 2024; Sheraz et al. 2024), while others highlight a heterogeneous effect of ETI on CO_2 emissions (e.g., Kartal, Shahbaz, et al. 2024; Kartal, Taşkın, et al. 2024).

The nexus between EPS and the environment also yields mixed results. Some studies find no significant link between EPS and environmental pollution (Tiwari, Mentel, et al. 2024), whereas others establish a positive nexus between EPS and environmental quality (e.g., Li et al. 2022; Wang et al. 2022; Fatima, Xuhua, Alnafisah, and Akhtar 2024).

In addition to ETI and EPS, a substantial body of research explores the effect of GDP, REU, and FDI on the environment. The literature generally supports theoretical expectations, showing that increases in GDP are often associated with higher CO_2 emissions (e.g., Sreenu 2022; Mirziyoyeva and Salahodjaev 2022) and EFP. Furthermore, recent studies on REU frequently demonstrate its effectiveness in reducing CO_2 emissions (e.g., Wang et al. 2023; Amin et al. 2024) and EFP (e.g., Akinsola et al. 2022; Javed et al. 2023; Shah and Ximei 2024). Similarly, extensive research on the link between FDI and the environment largely supports the pollution haven hypothesis (PLH), indicating that increased FDI often correlates with higher CO_2 emissions (e.g., Blanco et al. 2013) and EFP (e.g., Li et al. 2022).

In light of this empirical literature, this study is poised to make a significant contribution by examining the marginal effects of ETI and EPS, alongside GDP, REU, and FDI, through a comprehensive empirical analysis. The study employs EFP as the primary indicator and LCF as a robustness check to assess environmental progress, positioning it as a valuable addition to the existing body of research.

3 | Methods

3.1 | Data and Variables

This study aims to empirically investigate the role of energy, environmental, and economic policies in achieving SDG-13. In alignment with this objective, EFP is employed as the primary proxy indicator of the environment, consistent with the literature (e.g., Chu and Tran 2022; Usman and Radulescu 2022; Sohag et al. 2024), while LCF serves as an alternative proxy to ensure robustness (e.g., Altıntaş et al. 2023). The empirical analysis focuses on the E7 countries, which include leading emerging economies. Due to the absence of EPS data for Mexico and incomplete FDI and ETI data for Indonesia, the analysis is restricted to the remaining five E7 countries.

Data for EFP and LCF is sourced from GFN (2024), ETI data from UNCTAD (2024), EPS data from OECD (2024), and GDP and FDI data from WB (2024). Additionally, data on REU is obtained from the EI (2024). The study utilizes annual data from 2000 to 2020, reflecting the availability of ETI and EPS data. This timeframe is adopted to ensure the longest possible data series. To facilitate the analysis, logarithmic (Ln) transformations are applied to the variables to assess elasticities and uncover the marginal effects of various factors on the environment. The key information of the variables is shown in Table 2.

3.2 | Prediction Models

Using the variables outlined in Table 2, three prediction models are constructed to assess the marginal effects of different factors on EFP.

Model 1 considers the main control variables, including GDP, REU, and FDI, to examine their effect on the environment, as specified in Equation (1):

$$\mathrm{LnEFP} = f(\mathrm{LnGDP}, \mathrm{LnREU}, \mathrm{LnFDI}) \tag{1}$$

Model 2 incorporates ETI alongside the control variables to explore its effect on the environment, as shown in Equation (2):

$$\mathrm{LnEFP} = f(\mathrm{LnGDP}, \mathrm{LnREU}, \mathrm{LnFDI}, \mathrm{LnETI}) \tag{2}$$

Model 3 integrates EPS with the control variables to assess its effect on the environment, as presented in Equation (3):

$$\mathrm{LnEFP} = f(\mathrm{LnGDP}, \mathrm{LnREU}, \mathrm{LnFDI}, \mathrm{LnEPS}) \tag{3}$$

These models are employed to empirically analyze the influence of the selected factors on the environment. To verify the robustness of the findings, the study also applies the prediction models using LCF as an alternative indicator. The corresponding equations for these robustness checks are provided in Equations (4–6).

$$\mathrm{LnLCF} = f(\mathrm{LnGDP}, \mathrm{LnREU}, \mathrm{LnFDI}) \tag{4}$$

$$\mathrm{LnLCF} = f(\mathrm{LnGDP}, \mathrm{LnREU}, \mathrm{LnFDI}, \mathrm{LnETI}) \tag{5}$$

TABLE 2 | Variables.

Type	Symbol	Definition	Unit	Data source
Dependent	EFP	Ecological footprint*	Hectares	GFN (2024)
	LCF	Load capacity factor**	Index	
Independent	ETI	Energy transition index	Index	UNCTAD (2024)
	EPS	Environmental policy stringency	Index	OECD (2024)
Control	GDP	Gross domestic product	Constant USD	WB (2024)
	REU	Renewable energy use	Exajoules	EI (2024)
	FDI	Foreign direct investments	Current USD	WB (2024)

Note: * and ** denote the main dependent variable and the dependent variable for the robustness.

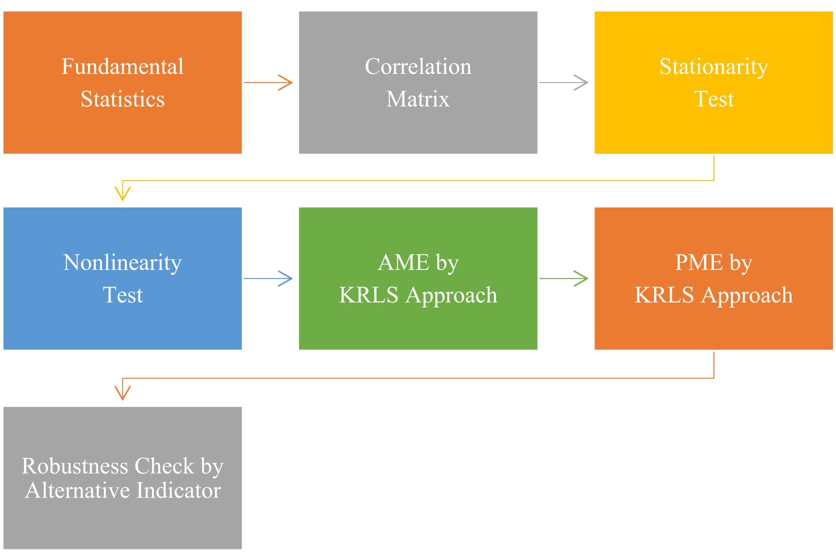

FIGURE 4 | Empirical process.

$$\text{LnLCF} = f(\text{LnGDP}, \text{LnREU}, \text{LnFDI}, \text{LnEPS}) \tag{6}$$

3.3 | Empirical Procedure

Figure 4 below presents the empirical process applied.

The empirical procedure consists of seven steps, beginning with fundamental statistics and progressing through correlations, stationarity, and nonlinearity tests, followed by the KRLS approach and a robustness test to validate the results. In the first step, the analysis focuses on the tendency, variation, symmetry, distribution, and normality of the data. The second step involves calculating bi-variate correlations to establish a basic nexus among variables. In the third and fourth steps, stationarity and nonlinearity are tested using the Phillips–Perron (PP) test (Phillips and Perron 1988) and the BDS test (Broock et al. 1996), respectively. The fifth and sixth steps involve applying the KRLS approach to obtain AME and PME, facilitating the identification of how independent variables influence EFP (Hainmueller and Hazlett 2014). Finally, the robustness check compares the KRLS results with EFP as the dependent variable against those using LCF as the dependent variable.

3.4 | KRLS Approach

The KRLS approach, developed by Hainmueller and Hazlett (2014), builds on regularized least squares, regularization networks, and kernel ridge regression, enabling flexible regression and classification without rigid assumptions (Saunders et al. 1998; Evgeniou et al. 2000; Cawley and Talbot 2002; Rifkin et al. 2003). Unlike generalized linear models, which depend on stringent distributional assumptions, KRLS derives its structure directly from the data, enhancing accuracy and reliability (Ferwerda et al. 2017). It offers three main advantages: (i) adaptability to data-driven functional forms, (ii) effective management of complex, nonlinear nexus with explicit variable effects, and (iii) a mathematical function that facilitates model interpretation.

The KRLS model is founded on two essential components: kernel fitting, which assesses the similarity between observations, and regularization, which mitigates overfitting. The Gaussian kernel is a common choice in this approach, as outlined by Hainmueller and Hazlett (2014).

$$K = k(x_j, x_i) = e^{-\frac{\|x_j - x_i\|^2}{\sigma^2}} \tag{7}$$

$$f(x) = \sum_{i=1}^{N} c_i k(x, x_i) \tag{8}$$

In Equation (7), x, σ, and $f(x)$ represent the observation vector, the standard deviation, and the target function. The term c_i in Equation (8) denotes the weight of covariate vectors. The KRLS approach incorporates regularization with a penalty term to control the complexity of the function and address overfitting:

$$\underset{f \in H}{\operatorname{argmin}} \sum_i \left(V(y_i, f(x_i))\right) + \lambda R(f) \tag{9}$$

Tikhonov regularization is frequently applied to solve the optimization problem defined in Equation (9), balancing model fit and complexity using the loss function $V(y_i, f(x_i))$, the regularizer R, and the trade-off parameter λ (Tikhonov 1963). The optimal solution is expressed in Equation (10).

$$\hat{c} = (K + \lambda I)^{-1} y \tag{10}$$

where I is the identity matrix and y is the result vector. Marginal effects of covariates are derived from pointwise partial derivatives using Equation (11), enabling the calculation of their effects at various points.

$$\frac{\partial \hat{y}}{\partial x_d} = -\frac{2}{\sigma^2} \sum_{i=1}^{N} \hat{c}_i k(x', x_i)(x'_d - x_{i,d}) \tag{11}$$

4 | Empirical Results and Discussion

4.1 | Fundamental Statistics

In the first step of the empirical process, the fundamental statistics presented in Table S1 reveal significant variations between variables across countries.

BRA exhibits a stable LnEFP and LnLCF with averages of 20.12 and 1.18, respectively, and minimal standard deviations (0.08 and 0.09), indicating minor fluctuations over time. Similarly, Brazil's economic indicator (LnGDP) has an average of 28.08 and a low variance (0.16), reflecting economic stability.

CHN has the highest average LnEFP of 22.06 among the countries, with a slightly higher standard deviation of 0.28, and the lowest average LnLCF (−1.27), highlighting its challenges in environmental sustainability. Economically, China has the highest average LnGDP at 29.58, underscoring its substantial economic scale, with low standard deviations across metrics indicating overall stability.

IND demonstrates a stable LnEFP with an average of 20.84 and a standard deviation of 0.21. Its average LnLCF (−0.98) is relatively low, indicating progress toward sustainability goals, while its LnGDP averages 28.04, with a higher standard deviation of 0.40.

RUS shows a balanced performance in LnEFP, with an average of 20.54 and a standard deviation of 0.04. Its positive LnLCF differentiates it from other countries. Economically, Russia's LnGDP averages 27.80, with a low standard deviation (0.20), indicating stability.

TUR has the lowest average LnEFP (19.25) among the countries, with a standard deviation of 0.17. Its average LnLCF is negative (−0.65) but shows low variability (0.14). Türkiye's LnGDP averages 27.65, with a standard deviation of 0.32, similar to Russia's. Jarque-Bera test results confirm that all metrics across these countries follow a normal distribution.

In the second step, the correlation matrix in Table S2 indicates a differentiated nexus between variables by country. In Brazil, LnLCF has a significant negative correlation with LnEFP

(−0.99), while LnGDP, LnFDI, and LnETI are positively correlated with LnEFP (0.78, 0.87, and 0.87, respectively). LnREU shows a moderate positive correlation (0.66). In China, India, and Türkiye, all independent variables have significant positive correlations with LnEFP and significant negative correlations with LnLCF. In Russia, similar to Brazil, LnLCF strongly negatively correlates with LnEFP (−0.84), while LnFDI, LnGDP, and LnETI exhibit moderate positive correlations (0.66, 0.47, and 0.45, respectively). However, the correlation between LnEFP versus LnREU and LnETI is weak.

The third step involves the PP stationarity test results shown in Table S3, revealing that all variables in Brazil and Türkiye are stationary at I(1) or I(2) levels. In contrast, certain variables such as LnEFP, LnGDP, and LnETI in China, LnREU in India, and LnEFP and LnGDP in Russia are stationary at the I(0) level, while others are stationary at I(1) or I(2) levels. The BDS nonlinearity test results in Table S4 indicate that all variables exhibit a nonlinear structure across the countries, except for LnEPS in Brazil (mixed structure) and LnEFP and LnLCF in Russia (linear structure).

4.2 | AME by KRLS Approach

In the fifth step of the empirical process, the KRLS approach is applied for each country to determine the effects of various independent variables (LnGDP, LnREU, LnFDI, LnETI, and LnEPS) on LnEFP. The results from each country's KRLS model output are summarized below:

The output of the KRLS model for BRA is given in Table 3.

TABLE 3 | AME for BRA.

Variable	Statistics	Models 1	2	3
LnGDP	Coef.	0.142	−0.027	0.069
	p	0.017	0.380	0.048
LnREU	Coef.	−0.044	−0.022	−0.026
	p	0.000	0.003	0.004
LnFDI	Coef.	0.027	0.014	0.035
	p	0.013	0.092	0.001
LnETI	Coef.		0.827	
	p		0.001	
LnEPS	Coef.			−0.012
	p			0.099
R^2		97.25	97.76	96.45

Table 3 indicates that common variables (LnGDP, LnREU, and LnFDI) significantly affect LnEFP in Models 1 and 3, but only LnREU is significant in Model 2. These results are consistent with the literature (e.g., Ahmed et al. 2020; Nathaniel et al. 2021; Akinsola et al. 2022). Notably, LnETI has a significant effect in Model 2, while LnEPS is insignificant in Model 3 (Pereira Jr et al. 2023). In the study of Wang et al. (2022), it is shown that EPS improves environmental quality. A 1% increase in LnGDP and LnFDI results in increases of 0.142% (0.069%) and 0.027% (0.035%) in LnEFP in Models 1 (Model 3), respectively. Besides, a 1% increase in LnREU causes a 0.044, 0.022, and 0.026 percentage-point decrease in Models 1, 2, and 3, respectively. On the other hand, the effect of LnETI in Model 2 on LnEFP is significant, while LnEPS in Model 3 has no significant effect on LnEFP. The models have R^2 values above 96%, indicating strong explanatory power, and thus these models can explain at least 96% of variations in LnEFP using the aforementioned independent variables.

The findings suggest that Brazil's economic growth is not eco-friendly due to fossil fuel dependency and noneco-friendly foreign investments, while REU is beneficial. The results imply that BRA does not have an eco-friendly economic growth structure due to its high fossil fuel dependency in the energy mix and lower per capita income, which is necessary to pass this threshold to benefit from income in ensuring environmental sustainability. Similarly, FDI, which comes to the country, is not helpful because the country has failed to attract eco-friendly foreign investments. This means that the investments coming to the country have been using noneco-friendly technologies, causing environmental degradation. On the other hand, renewable energy helps protect the environment, which means that renewable energy has been used efficiently and effectively to benefit. Conversely, energy transition and environmental stringency policy are not beneficial for BRA, which means the country should rework the energy transition and environmental policy frameworks.

The output of the KRLS model for CHN is given in Table 4.

Table 4 shows all variables significantly affecting LnEFP across the models, with positive effects for all variables. LnGDP has an effect ranging from 0.103 to 0.162, LnREU from 0.029 to 0.040, and LnFDI from 0.063 to 0.086. LnETI increases LnEFP by 0.605% and LnEPS by 0.035%. The R^2 values exceed 99%, demonstrating a strong explanatory capacity. The results indicate that China's GDP, REU, and policies are not eco-friendly, necessitating a comprehensive restructuring to support environmental sustainability.

As it is seen, all variables used in three different models statistically affect LnEFP in CHN. Contrary to the results obtained from BRA, all variables positively affect LnEFP in CHN. Specifically, the effect of LnGDP differs from 0.103 to 0.162 among models. For LnREU (LnFDI), this effect differs from 0.029 (0.063) to 0.040 (0.086) as well. Besides, it can be said that a 1% increase in LnETI (LnEPS) causes a 0.605 (0.035) percentage point increase in LnEFP in CHN. Similar results showing the importance of GDP, REU, and FDI on the environment are given in the studies in the literature as well (Arain et al. 2020; Fan and Hao 2020; Xu et al. 2022). In addition, in the studies of Bashir et al. (2024) and Tiwari, Mentel, et al. (2024), it is emphasized that ETI and EPS ensure environmental performance. Moreover, R^2 statistics are higher than 99%, showing these models can explain at least 99% of variations in LnEFP using the aforementioned independent variables. The results imply

TABLE 4 | AME for CHN.

Variable	Statistics	Models 1	2	3
LnGDP	Coef.	0.162	0.103	0.115
	p	0.000	0.000	0.000
LnREU	Coef.	0.040	0.029	0.032
	p	0.000	0.000	0.000
LnFDI	Coef.	0.086	0.063	0.065
	p	0.000	0.001	0.000
LnETI	Coef.		0.605	
	p		0.000	
LnEPS	Coef.			0.035
	p			0.002
R^2		99.53	99.58	99.59

TABLE 5 | AME for IND.

Variable	Statistics	Models 1	2	3
LnGDP	Coef.	0.207	0.156	0.167
	p	0.000	0.000	0.000
LnREU	Coef.	0.059	0.046	0.054
	p	0.000	0.000	0.000
LnFDI	Coef.	−0.023	−0.021	−0.013
	p	0.052	0.059	0.206
LnETI	Coef.		0.164	
	p		0.000	
LnEPS	Coef.			0.051
	p			0.057
R^2		99.40	99.37	99.36

that CHN does not sustain eco-friendly economic growth. Also, the current structure of REU, FDI, ETI, and EPS is not beneficial. It means that the country should completely restructure its economic growth structure, REU, foreign investment policy as well as energy transition and environmental policy frameworks so that these factors can be transformed in a reverse way, where they may have a supporting role on environmental sustainability.

The output of the KRLS model for IND is given in Table 5.

Table 5 reveals that LnGDP and LnREU significantly affect LnEFP in all models, while LnFDI and LnEPS in Model 3 do not. LnGDP's effect varies from 0.156 to 0.207, and LnREU's from 0.046 to 0.059. The R^2 values are over 99%. The findings suggest that India's economic growth and related policies are not eco-friendly, requiring a transformation to enhance environmental

TABLE 6 | AME for RUS.

Variable	Statistics	Models 1	2	3
LnGDP	Coef.	0.058	0.028	0.051
	p	0.011	0.047	0.006
LnREU	Coef.	−0.003	−0.006	−0.003
	p	0.476	0.099	0.390
LnFDI	Coef.	0.016	0.013	0.016
	p	0.001	0.002	0.000
LnETI	Coef.		0.295	
	p		0.024	
LnEPS	Coef.			0.008
	p			0.425
R^2		58.80	59.56	59.34

sustainability through improved use of renewable energy, foreign investment policies, and environmental strategies.

The effect of LnGDP and LnREU on LnEFP is statistically significant for all models in IND. However, LnFDI in all models and LnEPS in Model 3 have no significant effect on LnEFP, which is not in line with the literature that Yirong (2022) shows the EPS improves the environmental quality in the long run. Contrary to the literature, it is shown that FDI has no significant effect on environmental quality in IND (Yirong 2022). In detail, an increase in LnGDP, LnREU, and LnETI causes an increase in LnEFP as well, which is in line with the literature (Ren et al. 2020; Sreenu 2022). Specifically, the effect of LnGDP differs from 0.156 to 0.207 among models. For LnREU, this effect differs from 0.046 to 0.059. In addition, R^2 statistics are higher than 99%, indicating these models can explain at least 99% of variations in LnEFP using independent variables.

The results imply that the economic growth model of IND is not eco-friendly. Also, REU, FDI, ETI, and EPS are not in good condition, which means that the country should completely transform its economic growth model, use of renewable energy, approach to foreign investments, energy transition, and environmental policies. Only in a comprehensive transformation can the country benefit from the aforementioned factors in supporting environmental sustainability.

The output of the KRLS model for RUS is given in Table 6.

Table 6 indicates that all variables except LnREU and LnEPS positively affect LnEFP. LnGDP's effect ranges from 0.028 to 0.058, and LnFDI's from 0.013 to 0.016. LnETI has a significant effect of 0.295%. The R^2 values around 59% suggest moderate explanatory power. The results imply that Russia's economic growth and policies are not environmentally sustainable, highlighting the need for restructuring to make these factors more eco-friendly.

Table 6 indicates that all variables except LnREU and LnEPS positively affect LnEFP in RUS. LnGDP's effect ranges from

0.028 to 0.058, and LnFDI's from 0.013 to 0.016. LnETI has a significant effect of 0.295%, implying that a 1% increase in LnETI causes a 0.295 percentage-point increase in LnEFP in RUS. These results are also emphasized in the studies in the literature as well (Mirziyoyeva and Salahodjaev 2022; Pavel et al. 2024). On the other hand, in the study of Liu et al. (2023), it is revealed that EPS and REU have a significant role in environmental quality, which is insignificant in this study. In addition, the R^2 values around 59% suggest moderate explanatory power, showing these models can explain 59% of variations in LnEFP using the aforementioned independent variables.

TABLE 7 | AME for TUR.

Variable	Statistics	Models		
		1	2	3
LnGDP	Coef.	0.292	0.121	0.218
	p	0.000	0.000	0.000
LnREU	Coef.	0.006	0.007	0.004
	p	0.182	0.065	0.201
LnFDI	Coef.	−0.005	−0.013	−0.002
	p	0.695	0.209	0.843
LnETI	Coef.		1.057	
	p		0.000	
LnEPS	Coef.			0.032
	p			0.124
R^2		98.67	98.91	97.89

The results imply that Russia's economic growth and policies are not environmentally sustainable, highlighting the need for restructuring to make these factors more eco-friendly.

The output of the KRLS model for TUR is given in Table 7.

Table 7 shows that only LnGDP and LnETI significantly affect LnEFP. LnGDP's effect varies from 0.121 to 0.292, and LnETI causes a 1.057% increase in LnEFP. Several studies show that GDP negatively affects environmental quality (Abumunshar et al. 2020; Abbasi et al. 2022). Besides, contrary to the study of Wang et al. (2020), LnEPS is found as insignificant in the study. The R^2 values exceed 97%, indicating strong model reliability. The results suggest that Türkiye's economic growth and related policies do not support environmental sustainability, requiring a transformation in economic, renewable energy, and investment policies.

4.3 | PME by KRLS Approach

In the sixth step, the partial marginal effects (PME) on EFP derived from the KRLS approach are visualized for each country in Figures 5–9. These visualizations offer a detailed view of how each independent variable—LnGDP, LnREU, LnFDI, LnETI, and LnEPS—marginally affects EFP in each country and also provide further insights into the marginal effects of the independent variables on LnEFP across the countries.

These analyses underscore the need for targeted policy interventions in each country to enhance environmental sustainability, focusing on REU, eco-friendly investments, and effective environmental policies.

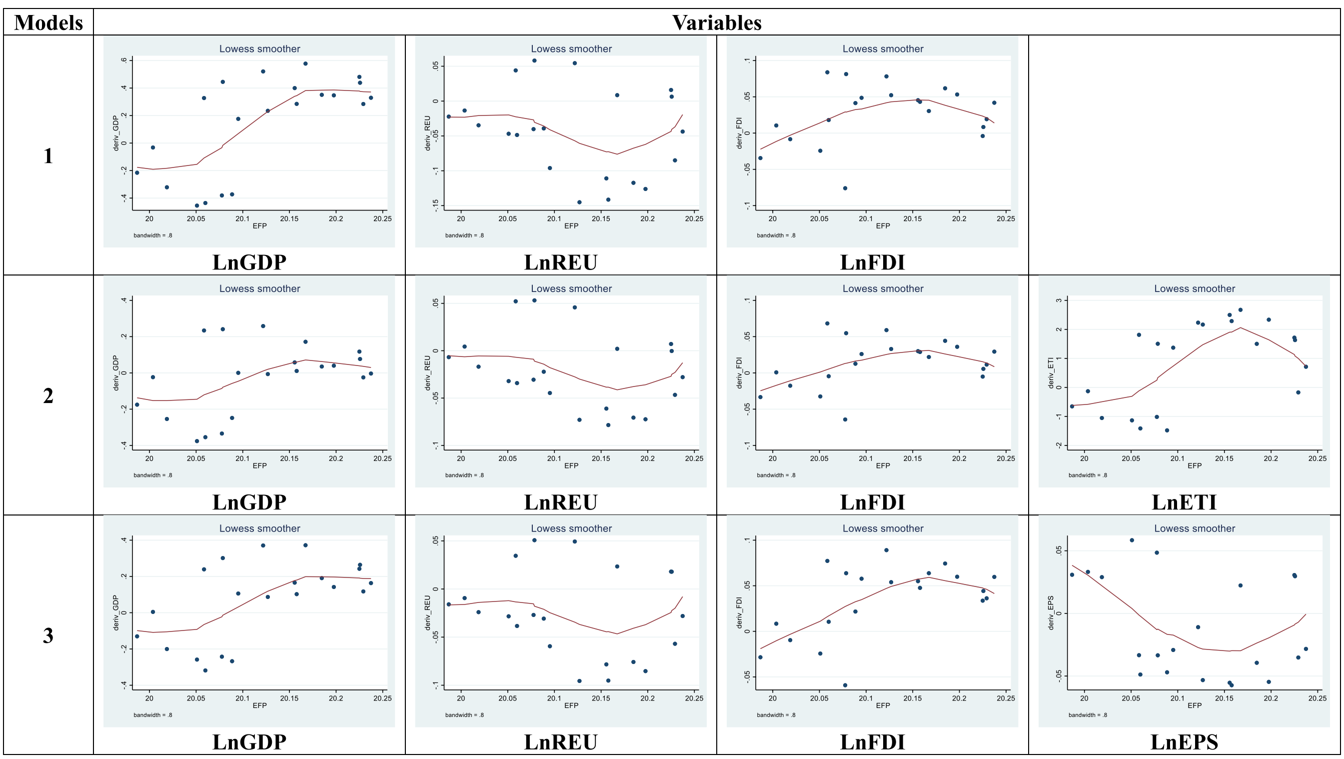

FIGURE 5 | PME for BRA. In graphs, the x-axis denotes EFP and the y-axis denotes the marginal effect of the variable.

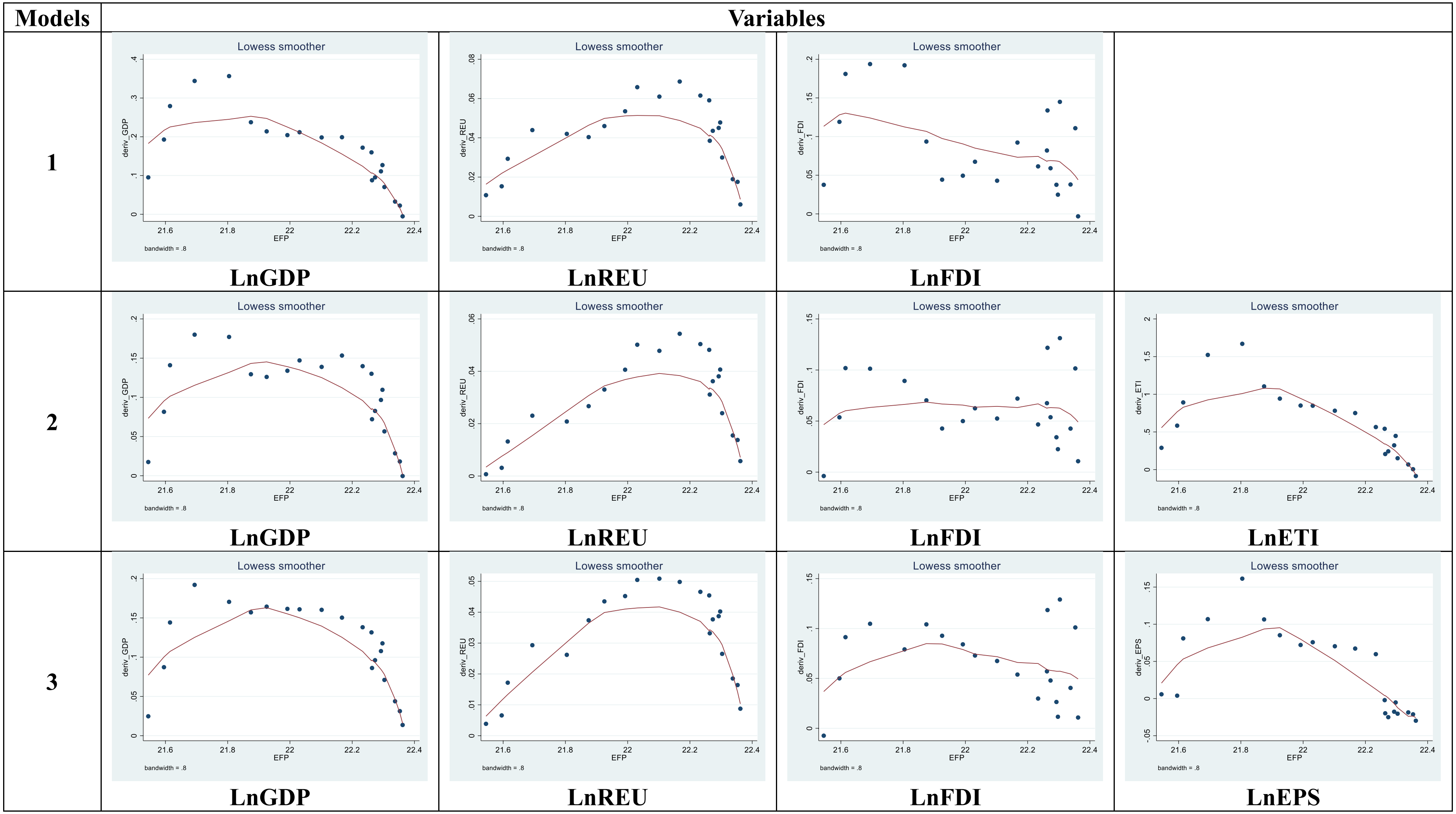

FIGURE 6 | PME for CHN. In graphs, the x-axis denotes EFP and the y-axis denotes the marginal effect of the variable.

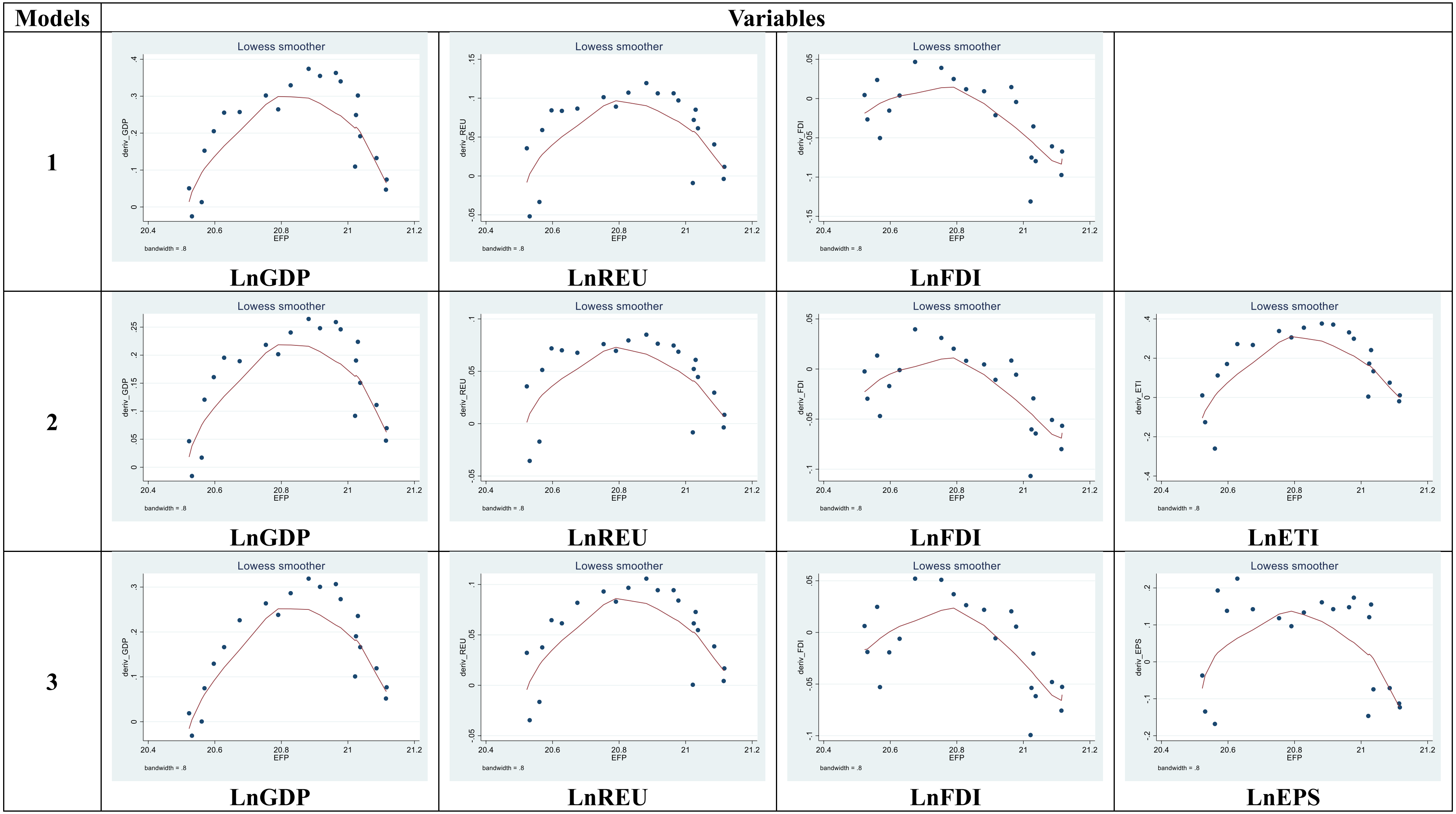

FIGURE 7 | PME for IND. In graphs, the x-axis denotes EFP and the y-axis denotes the marginal effect of the variable.

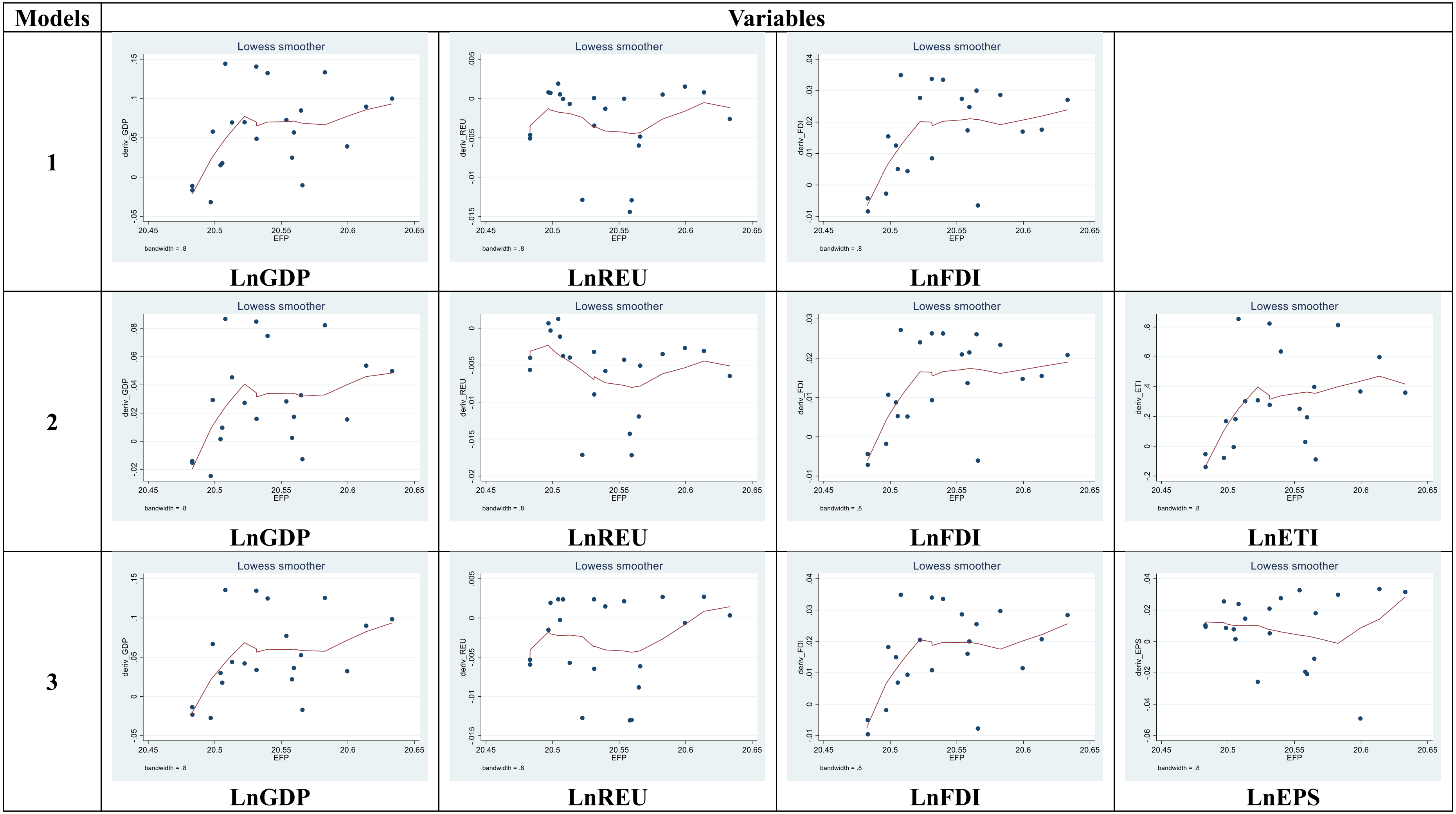

FIGURE 8 | PME for RUS. In graphs, the *x*-axis denotes EFP and the *y*-axis denotes the marginal effect of the variable.

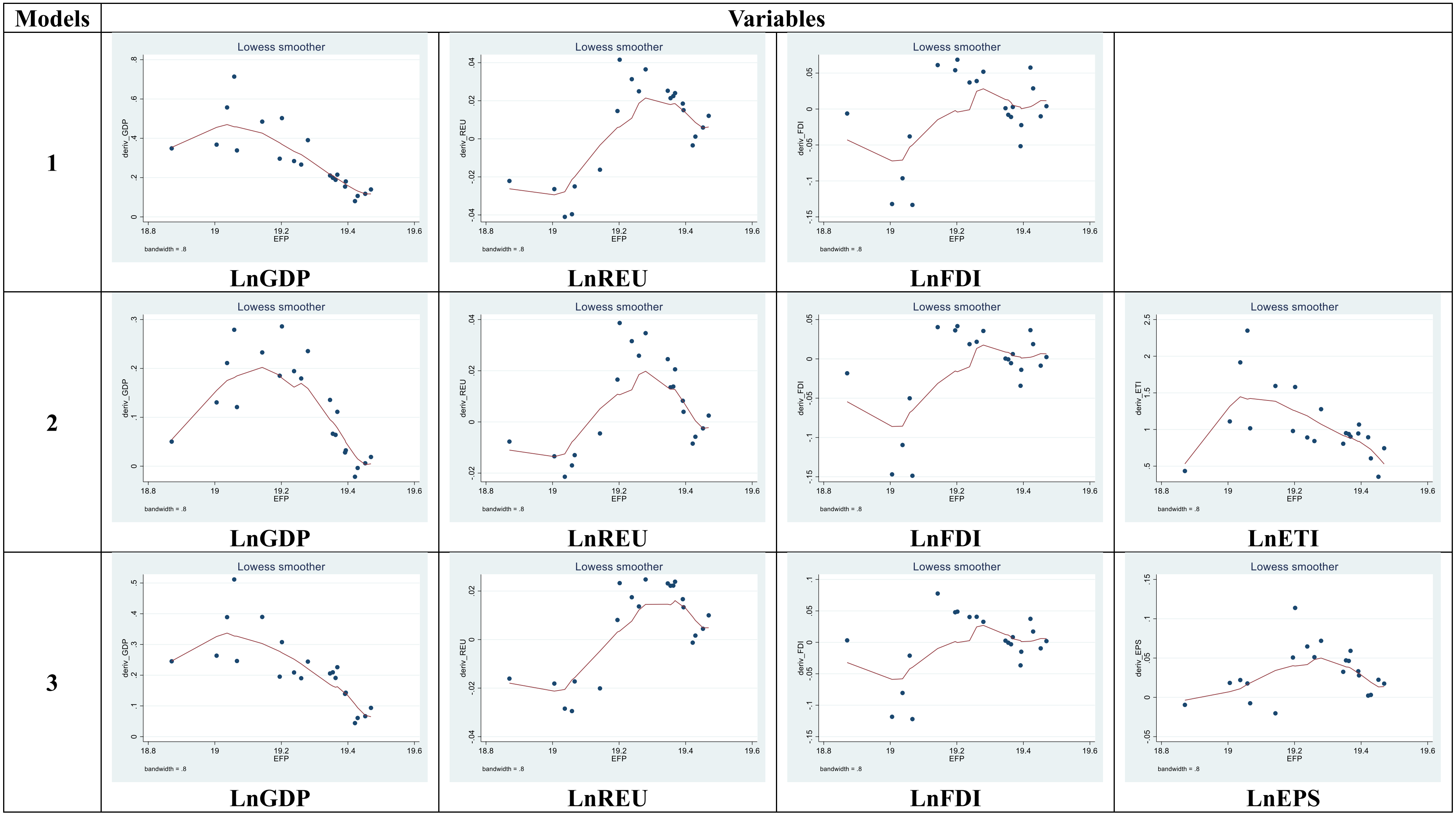

FIGURE 9 | PME for TUR. In graphs, the x-axis denotes EFP and the y-axis denotes the marginal effect of the variable.

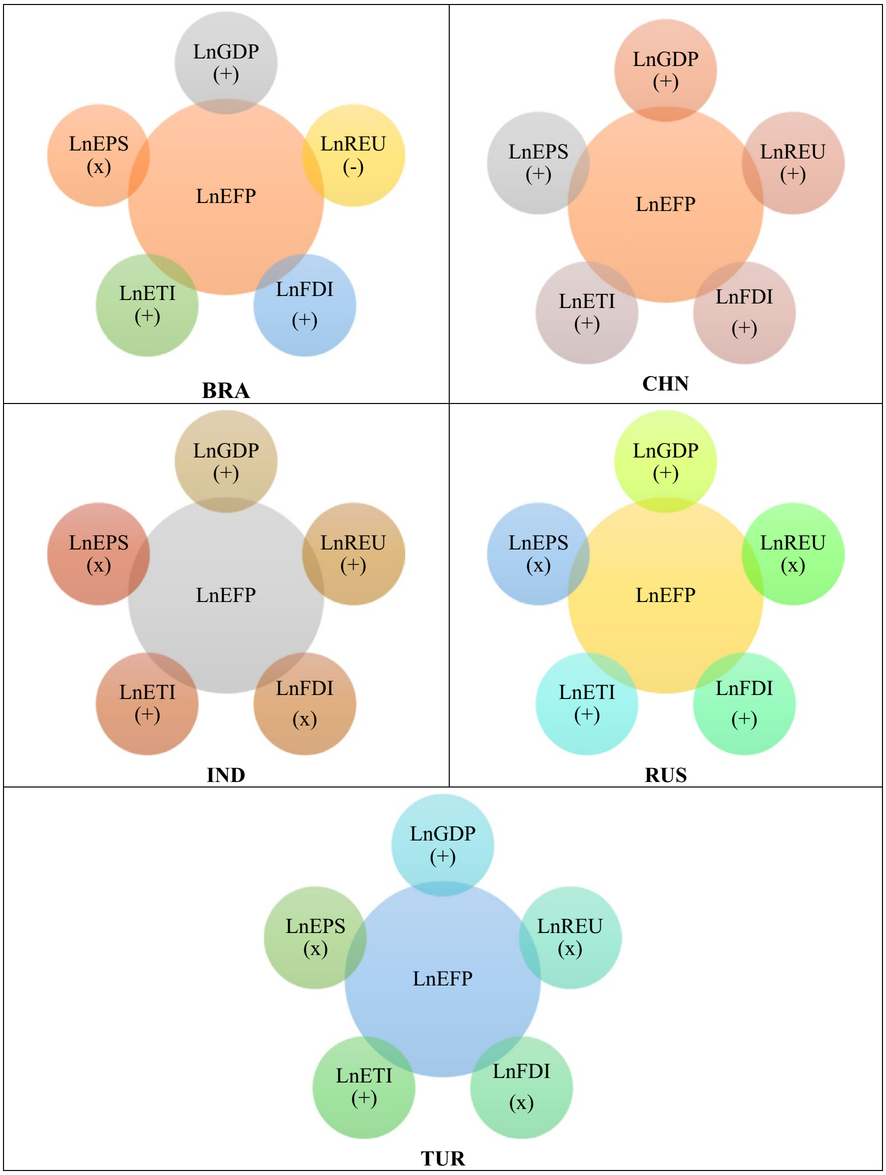

FIGURE 10 | Summary of the results. +, −, and *x* denote the increasing, decreasing, and insignificant effects on EFP, in order.

In Figure 5 for BRA, the analysis indicates that across all three models, as LnEFP increases, the negative effect of LnGDP diminishes. However, beyond a threshold value of 20.1 for LnEFP, the effect of LnGDP turns positive and subsequently intensifies. Regarding LnREU, the nexus is negative and nonlinear, exhibiting a U-shaped trajectory after the 20.07 level of LnEFP across the models. In contrast, the association between LnREU and LnEFP reveals a positive and n-shaped pattern, where the effect increases until the 20.15 LnEFP level but declines thereafter. Furthermore, in Model 2, the nexus between LnETI and LnEFP mirrors that of LnFDI and LnEFP, albeit with a relatively higher magnitude for LnETI. Meanwhile, in Model 3, LnEPS exhibits a declining marginal effect up to the 20.05 LnEFP threshold; beyond this point, its negative influence intensifies, peaking at the 20.15 level.

In Figure 6 for CHN, across all models, the PME of LnGDP initially increases with LnEFP but diminishes at higher levels, forming an n-shaped curve. This suggests a positive association between LnGDP and LnEFP up to a threshold of 21.9, after which the effect weakens. LnREU follows a similar n-shaped trajectory, with PME rising initially but declining beyond the 22.2 level of LnEFP. This indicates a reduction in LnREU's effect at higher LnEFP levels. LnFDI exhibits a generally decreasing trend, with PME diminishing as LnEFP rises. LnETI and LnEPS, analyzed in Models 2 and 3 respectively, also exhibit n-shaped patterns, wherein their PME increases initially but declines at higher LnEFP levels.

In Figure 7 for IND, all independent variables across the three models demonstrate an n-shaped nexus with LnEFP. This pattern implies that the PME of LnGDP, LnREU, LnFDI, LnETI, and LnEPS is significant at lower and moderate LnEFP levels but weakens and declines beyond the 20.8 LnEFP threshold across all models.

In Figure 8 for RUS, the analysis reveals an upward trend in LnGDP across all three models, with PME increasing alongside LnEFP. LnREU exhibits a fluctuating pattern, where PME initially increases negatively before declining at higher

LnEFP levels. Similarly, the PME of LnFDI on LnEFP shows an upward trend up to the 20.52 LnEFP level, beyond which its effect stabilizes. In Model 2, LnETI demonstrates a steady increase in PME, indicating its positive contribution to LnEFP. Finally, in Model 3, LnEPS follows a positive trajectory, with PME rising as LnEFP increases, signifying the growing effectiveness of stringent environmental policies in managing ecological effects.

In Figure 9 for TUR, across all models, LnGDP exhibits a positive nexus with LnEFP, peaking at approximately 19.1 LnEFP before declining. LnREU consistently shows an upward trend, signifying a direct positive correlation with LnEFP. Conversely, LnETI and LnEPS exhibit nonlinear patterns, peaking at around 19.0 and 19.3 LnEFP, respectively, before sharply declining.

As a result, the results underscore the nonlinear and dynamic interactions between economic, environmental, and policy variables and their effects on EFP. Threshold effects are evident for many variables, such as LnGDP, LnREU, LnFDI, LnETI, and LnEPS, where their positive contributions diminish or reverse beyond specific LnEFP levels. While Brazil and India exhibit similar n-shaped trends for key variables, China and Russia show unique patterns reflecting their distinct economic and environmental dynamics. Türkiye, on the other hand, demonstrates a relatively balanced trajectory, with positive PME effects peaking before tapering off. These findings highlight the complex interplay of economic activities, resource utilization, foreign investments, environmental taxation, and policy enforcement in shaping ecological effects globally.

4.4 | Robustness Check

In the study, the analyses are repeated using LnLCF instead of LnEFP as the dependent variable for the robustness check. Based on the model output, where LnLCF is the dependent variable, the signs of the coefficients obtained from the independent variables are expected to be opposite to those in the models where LnEFP is the dependent variable.

The robustness check demonstrates that the signs of coefficients reverse consistently across all explanatory variables when switching from LnEFP to LnLCF, as expected, confirming that the observed nexus in the original models is not due to random chance or spurious correlations (see Table S5–S9). Most explanatory variables remain statistically significant in both models, further reinforcing the consistency and reliability of the findings. Both models exhibit high R^2 values, indicating strong explanatory power. This suggests that robustness is confirmed regardless of minor variations in model fit.

As a second step in the robustness check, the PME graphs obtained from the model with LnEFP as the dependent variable were compared to those from the model with LnLCF as the dependent variable (see Figures S1–S5). In general, it was revealed that the PME of LnLCF shows a horizontally inversely symmetric distribution compared with LnEFP. Specifically, variables with an n-shaped distribution in the LnEFP model exhibit a u-shaped distribution in the LnLCF model, and vice versa.

Overall, the reversal of signs, combined with consistent significance and strong explanatory power, validates the original model's findings, ensuring that the observed nexus is robust and independent of the specific dependent variable used.

4.5 | Empirical Summary

The empirical analysis results are summarized in Figure 10, detailing the effect of independent variables on LnEFP across the countries.

In Brazil, key factors such as LnGDP, LnETI, and LnFDI exhibit a positive and significant effect on LnEFP, highlighting their crucial role in shaping the environment. However, LnREU demonstrates a negative influence, suggesting that rising levels of renewable energy utilization may not have an immediate beneficial effect in this context. Notably, LnEPS appears to have no significant effect on LnEFP in Brazil, indicating that environmental policy or energy standards may not directly influence financial performance in the Brazilian market.

In China, the nexus between all independent variables and LnEFP is uniformly positive, underscoring the country's broader trend toward integrating economic growth, technological innovation, and foreign direct investment in its pursuit of an improved environment. Similarly, both India and Russia display a nonsignificant effect of LnEPS on LnEFP, reinforcing the notion that energy policy frameworks may not be as influential in these regions as they are in others. Moreover, in India, LnFDI does not significantly affect LnEFP, while in Russia, it is the LnREU that fails to show a meaningful nexus with environmental financial performance. Nevertheless, all other variables in these countries demonstrate a positive effect on LnEFP, suggesting that economic development and technological advancements continue to support environmental improvements.

In Türkiye, the analysis reveals that both LnGDP and LnETI positively influence LnEFP, signaling that economic growth and technology adoption play pivotal roles in the country's environmental financial trajectory. However, the effect of LnEPS, LnREU, and LnFDI is not significant, indicating that, at least in the current context, energy policies, renewable energy usage, and foreign direct investment do not substantially affect environmental financial performance in Türkiye. This nuanced understanding of the diverse factors influencing LnEFP across different nations provides valuable insights into the complexities of environmental sustainability concerning economic and technological variables.

4.6 | Discussion and Policy Implications

Utilizing a comprehensive theoretical and empirical framework, this study examines how SDG-13 can be achieved through policies related to energy, the environment, and the economy. Employing the KRLS approach on data from 2000 to 2020 for five leading emerging countries, the study investigates the effects of variables such as GDP, REU, FDI, ETI, and EPS on environmental progress, primarily measured by EFP and alternatively by LCF for robustness. The findings reveal that FDI and

GDP do not contribute to environmental quality improvements in these countries (Javorcik and Wei 2003), whereas REU only enhances environmental quality in Brazil (Hasanov et al. 2021). ETI and EPS do not facilitate environmental quality improvements in any of the countries studied (Sarkodie 2021; Kartal, Ayhan, and Ulussever 2024). The KRLS approach achieves high predictive accuracy, with models reaching 99.6%, offering new insights into average and marginal effects, which can inform policy implications for achieving SDG-13 in these emerging countries.

The study indicates that energy transition policies have not effectively reduced environmental degradation in the analyzed countries. Despite some progress, particularly in India and Russia, current energy transition frameworks need restructuring to be more beneficial and eco-friendly. Policymakers should comprehensively assess their energy mix and potential clean energy alternatives, developing short-, medium-, and long-term plans to transition from fossil fuels to cleaner energy sources. Addressing potential displacements among clean energy sources is crucial to ensure successful energy transitions (Kartal, Depren, and Ayhan 2024).

Regarding EPS, the current frameworks in the studied countries have not significantly reduced environmental degradation. Countries like China and Türkiye show increasing trends, but the existing EPS frameworks are insufficient. Policymakers need to critically examine and strengthen environmental policies to reduce EFP and improve environmental quality. By addressing inefficient practices and gaps in current policies, these countries can restructure EPS practices to benefit environmental quality (Kartal, Ayhan, and Ulussever 2024).

Economic growth (GDP) has not been leveraged effectively to enhance environmental quality in the studied countries, indicating that their growth models are not eco-friendly. Contributing factors include high fossil fuel use, noneco-friendly production materials, and low technology levels. Transforming economic growth models to be eco-friendly by enhancing energy transitions, increasing EPS, and using cleaner energy sources is essential to support environmental progress.

Only Brazil benefits from REU in improving environmental quality, while other countries with rich clean energy resources have failed to do so due to a high dependence on fossil fuels. Increasing the share of renewable energy in the total energy mix through financial and fiscal incentives, further sector electrification, fossil fuel taxes, and mandates for clean energy use can enhance environmental quality.

Despite significant FDI inflows, the countries studied do not benefit environmentally from FDI, indicating the presence of PHH. Implementing measures to ensure FDI contributes positively to environmental quality is essential to shift from PHH to PLH, where FDI becomes beneficial for host countries.

Across all countries considered (Brazil, China, India, Russia, and Türkiye), there is a general lack of positive environmental effects from GDP, REU, FDI, ETI, and EPS. Only Brazil shows some success with REU. Therefore, these countries need to reevaluate and restructure their economic growth models, renewable energy usage, FDI flows, energy transition policies, and environmental policies to foster eco-friendly effects.

The KRLS approach reveals that the effects of these variables on environmental progress vary across countries and percentiles, emphasizing the importance of considering nonlinear effects in policy modeling. Continuous monitoring and consideration of these differentiating effects are critical for effective policymaking.

5 | Conclusion

Addressing climate change and its associated challenges is paramount for safeguarding the future of our planet. Identifying the root causes of negative environmental progress is essential for developing appropriate solutions. This study contributes to the existing literature by examining both traditional (GDP, REU, FDI) and recently emerged (ETI, EPS) factors influencing environmental degradation, with a focus on achieving SDG-13 through energy, environment, and economy-related policies.

Analyzing data from 2000 to 2020 using the KRLS approach, the study focuses on five leading emerging countries (Brazil, China, India, Russia, and Türkiye), which together accounted for 45.26% of global CO_2 emissions in 2020 (EI 2024). The findings indicate that these countries have not effectively leveraged GDP, REU, FDI, ETI, or EPS to decrease EFP or increase LCF, highlighting the need for substantial policy reform to improve environmental quality and support climate action.

The study's empirical results underscore the nonlinear effects of these factors on environmental progress, necessitating a nuanced approach to policy development. By integrating these insights into policy frameworks, countries can better align their strategies with the goals of SDG-13. The study also highlights the need for future research to explore additional factors, such as R&D investments, environmental taxes, and governance, and to use more recent data and advanced econometric techniques for a deeper understanding of these dynamics.

In conclusion, this study provides valuable insights and practical recommendations for policymakers aiming to enhance environmental quality through targeted economic and environmental strategies, contributing to the broader effort to combat climate change.

By relying on the empirical results obtained, the study elaborates on various policy implications. These include supporting energy transition through short-, medium-, and long-term strategies, addressing inefficiencies in environmental policies, transforming economic growth models by leveraging energy transitions and stringent environmental policies, enhancing clean energy installation and utilization, and regulating FDI flows to attract environmentally beneficial investments. The study underscores the importance of considering nonlinear and marginal effects in policy frameworks and restructuring current energy, environmental, and economic policies to support climate action and environmental preservation.

While this research offers novel insights, it acknowledges certain limitations. Focusing on leading emerging economies within the E7 block, future research could expand to include countries in other groups such as BRICS, MINT, or those participating in the Belt and Road Initiative. Comparative analyses of both emerging and developed nations could also test the broader applicability of these findings.

Additionally, while this study examines key factors, future research could incorporate other variables such as R&D investments, patents, environmental taxes, and country risk to assess their marginal effects. Future studies might also concentrate on decarbonization, using CO_2 emissions as the primary environmental proxy.

Employing more recent data and alternative econometric techniques (e.g., WLMC, Fourier-based, and quantile-based approaches) could provide deeper insights, particularly regarding recent developments such as energy crises. Disaggregated data at sectoral levels could reveal variations across economic sectors, and emerging factors like artificial intelligence, competition, environmental regulations, ESG, governance, and innovation could be explored for their effects on the environment. These approaches would extend the understanding of average and pointwise marginal effects, contributing to a more nuanced perspective on environmental policy and climate action. Finally, some recently emerged factors, such as artificial intelligence (Wang, Li, and Li 2024; Wang, Zhang, et al. 2024; Wang et al. 2025), competition (Liao and Liu 2024; Liao et al. 2024), environmental regulations (Liao and Zhang 2024), ESG (Yadav et al. 2024; Huang et al. 2025), governance (Naimoğlu et al. 2025), and innovation (Liao 2018; Shen et al. 2020), would be considered in new research. By including these points, new studies can make an average and pointwise marginal effect analysis on new concepts, which may result in extending the knowledge further.

Author Contributions

The authors have contributed equally to this work. All authors read and approved the final manuscript.

Acknowledgments

The authors have nothing to report. Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Disclosure

The authors have nothing to report.

Consent

The authors are willing to permit the Journal to publish the article.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available on request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.