Haseeb et al. Discover Sustainability (2026) 7:391
https://doi.org/10.1007/s43621-025-02471-4

RESEARCH Open Access

Asymmetric effects of economic policy uncertainty, natural resources, and foreign investment on ecological sustainability

Mohammad Haseeb[1,2], Md. Emran Hossain[3,4], Mohd Shuaib[1], Md Mostafa Jalal[5], Samariddin Makhmudov[6,7,8] and Mohammed Alnour[9,10*]

*Correspondence:
Mohammed Alnour
mohamedmershing88@gmail.com

Full list of author information is available at the end of the article

Abstract
The escalating challenges of environmental degradation and climate change are amplifying global uncertainties, posing significant risks to food security, water availability, and biodiversity. This study examines the asymmetric effects of economic policy uncertainty, economic growth, foreign direct investment, and natural resources on environmental quality in Saudi Arabia over the period from 1995 to 2024. Employing a robust set of econometric techniques—including unit root tests, cointegration tests, nonlinear autoregressive distributed lag (NARDL) modeling, and the Wald test—this research provides a comprehensive empirical analysis. The NARDL results indicate that positive shocks in economic policy uncertainty and economic growth significantly degrade environmental quality, as measured by the ecological footprint, while positive shocks in foreign direct investment and natural resource rents enhance environmental quality in the long run. Conversely, negative shocks in economic policy uncertainty and foreign direct investment improve environmental quality, whereas negative shocks in economic growth and natural resources exacerbate environmental degradation over the long term. Based on these findings, the study proposes targeted policy recommendations for Saudi Arabian policymakers to promote sustainable development and mitigate environmental pressures, aligning with the objectives of Vision 2030.

Keywords Ecological footprint, Economic uncertainty, Economic growth, FDI, Natural resources, Saudi Arabia

1 Introduction

Environmental pollution, driven by rapid economic growth, threatens biodiversity, depletes natural resources, and exacerbates climate change, air pollution, and global warming [17, 41, 63]. Saudi Arabia, a key player in the Middle East, leverages its vast oil reserves to fuel economic development and geopolitical influence, but this has increased its ecological footprint through resource extraction, industrialization, and high energy consumption [34, 80]. In response, Saudi Arabia's Vision 2030 aims to reduce emissions and promote sustainable development. However, achieving the Sustainable

Development Goals (SDGs), particularly SDG 13, remains challenging, as CO_2 emissions must decrease by 45% by 2030 and reach net-zero by 2050 (SDG Report, 2022). This study investigates innovative strategies to balance economic growth with environmental sustainability in Saudi Arabia in the era of policy uncertainty.

Theoretically, economic policy uncertainty (EPU) can affect the environment in several ways. First, heightened uncertainty may prompt producers to rely on conventional, environmentally harmful production methods, thereby accelerating environmental degradation. Second, EPU can disrupt investment and consumption patterns, which may further contribute to environmental deterioration. Third, increased uncertainty often leads to reductions in research and development, renewable energy adoption, and technological innovation, all of which are critical for environmental sustainability. Therefore, understanding the relationship between EPU and environmental degradation is essential for designing effective environmental policies. Empirically, several studies have highlighted the link between EPU and the environment through various channels. For instance, Danish et al. [29] found that EPU increases energy consumption, which in turn raises pollution levels in both the short and long term. Similarly, Jiang et al. [46] observed that economic agents may delay or alter decision-making under high uncertainty, thereby exacerbating environmental degradation in the United States. Adams et al. [2] also concluded that EPU has a negative effect on environmental quality. In contrast, Adedoyin and Zakari [4] reported that EPU could reduce economic growth and energy use in the short term, potentially lowering pollution levels. These findings suggest that EPU can influence environmental quality in both positive and negative ways, depending on the context.

Researchers continue to explore the various factors that influence environmental quality. Key determinants identified in the literature include gross domestic product [56], per capita income (Nathaniel & Bekun, 2020), foreign direct investment [52], energy consumption [8], urbanization [39, 40], human capital development [49], financial development [23], natural resource use [48], trade openness [78], population growth [74], institutional quality (Dada et al., 2021), and technological innovation [85], among others. Each of these variables exerts distinct and sometimes conflicting effects on environmental pollution. This study focuses on examining the impacts of economic growth, foreign investment, and natural resources on environmental quality. Numerous studies suggest that economic growth tends to degrade environmental conditions [3, 70]. Meanwhile, foreign investment has shown both positive and negative environmental effects, depending on the context [57, 59]. The relationship between natural resources and environmental quality has garnered particular interest, as it can also yield mixed outcomes [7, 89]. Overall, the literature indicates that economic development, foreign investment, and natural resource utilization are critical factors in shaping environmental outcomes.

As Saudi Arabia pursues its economic development goals, it faces significant challenges arising from EPU, a factor that notably influences both domestic and international stakeholders. The stability and predictability of environmental and economic policies are crucial for attracting investment, sustaining long-term growth, and advancing economic diversification. At the same time, the country is actively seeking foreign investment to support its transition toward a more diversified, knowledge-based economy. The success of this transition relies on a balanced mix of infrastructure development, policy consistency, and market accessibility. However, economic expansion often leads to increased exploitation of natural resources, which in turn contributes to environmental degradation. Against this backdrop, the present study aims to examine the effects of EPU and related factors on Saudi Arabia's ecological footprint.

This study offers several dimensions of novelty. First, there is a notable gap in the existing literature concerning the impact of EPU on the ecological footprint in the context of Saudi Arabia. Most prior research on the nexus between policy uncertainty and environmental quality has relied on panel or regional data analyses, while evidence from resource-dependent economies such as Saudi Arabia remains limited. Second, previous research that examined the relationship between EPU and the environment in resource-based economies has largely relied on partial measures of environmental quality, such as CO_2 emissions. However, CO_2 emissions capture only air pollution. To provide a more comprehensive assessment, the present study employs the ecological footprint as a proxy for overall environmental quality. Third, this study employs the asymmetric ARDL approach to examine the long- and short-run impacts of positive and negative shocks to EPU, economic growth, FDI, and natural resources on Saudi Arabia's ecological footprint. This method offers deeper insights into asymmetric relationships, thereby enabling more nuanced policy implications. The findings are expected to provide valuable guidance not only for Saudi Arabia but also for other developing and developed countries facing high ecological deficits. Fourth, existing literature has largely relied on the EPU index developed by Baker et al. [21]. While this index is a useful measure of economic policy uncertainty, its exclusion of political uncertainties and lack of country-specific foundations make it a questionable tool for capturing uncertainty from a comprehensive perspective. These limitations may result in issues of accuracy, bias, and reliability. To address this shortcoming, the current study employs the World Uncertainty Index (WUI), developed by Ahir et al. [5], which is based on Economist Intelligence Unit (EIU) country reports for 143 economies. The WUI is considered more comprehensive, as it incorporates both political and economic uncertainties.

Based on the empirical findings, the study offers key policy recommendations. Policymakers should focus on reducing economic policy uncertainty, as it delays economic progress and hampers environmental sustainability. Under uncertain economic conditions, industrial leaders may overexploit natural resources, exacerbating environmental degradation. Ensuring policy stability can help mitigate pollution and support sustainable development. Additionally, political stability plays a vital role in reinforcing the legitimacy and effectiveness of environmental regulations.

The remainder of this study is organized as follows: Sect. 2 provides a comprehensive review of the relevant literature and theoretical framework. Section 3 outlines the data, variables, and methodological framework employed in the analysis. Section 4 presents and discusses the empirical results. Finally, Sect. 5 concludes the study with key findings and offers novel policy implications.

2 Literature review

2.1 Theoretical framework

The theoretical foundation of this study is rooted in the Ecological Modernization Theory (EMT), which posits that economic development and technological advancements can decouple environmental degradation from growth, fostering sustainable practices through policy reforms and innovation [54]. In the context of Saudi Arabia, a resource-rich economy heavily reliant on oil exports, EMT provides a lens to examine how economic policy uncertainty (EPU), natural resources (NR), and foreign direct investment (FDI) influence ecological sustainability. Saudi Arabia's Vision 2030 initiative exemplifies EMT by aiming to diversify the economy beyond hydrocarbons, reduce resource dependency, and promote green investments. However, the interplay of these variables may exacerbate or mitigate environmental pressures, as suggested by the Treadmill of Production Theory, which argues that relentless economic expansion driven by resource extraction and capital inflows perpetuates ecological overshoot unless counterbalanced by robust policies [66]. This framework underscores the need to investigate asymmetric effects, where positive and negative shocks in EPU, NR, and FDI may disproportionately impact EFP due to path dependencies in environmental systems.

Building on the Pollution Haven Hypothesis (PHH) and Pollution Halo Hypothesis (PHH), the study theorizes that FDI can have dual effects on ecological sustainability. The former suggests that developing economies like Saudi Arabia attract pollution-intensive industries from abroad, increasing EFP through lax regulations [26], while the latter proposes that FDI transfers clean technologies and management practices, potentially reducing environmental footprints [87]. Similarly, NR abundance aligns with the Resource Curse Hypothesis, where overreliance on rents from oil and minerals stifles diversification and innovation, leading to heightened ecological degradation [16]. EPU, drawing from uncertainty aversion in behavioral economics, amplifies these dynamics by deterring long-term green investments and encouraging short-term resource exploitation during policy volatility [21]. In Saudi Arabia, where economic growth (GDP) is intertwined with oil revenues, these factors may asymmetrically affect ecological sustainability, as positive shocks (e.g., resource booms) could lock in unsustainable patterns, while negative shocks (e.g., policy stabilization) enable corrective measures.

Theoretically, the research on the nexus between economic activity and environmental quality for decades has been grounded in the Environmental Kuznets Curve (EKC) hypothesis, which posits that this relationship follows an inverted U-shaped pattern [38]. In specific, at the early stages of economic growth, development typically generates higher levels of waste and pollution because it requires greater resource consumption,this phenomenon is known as the scale effect. However, as an economy advances and surpasses a certain income threshold (the turning point), environmental quality begins to improve. This occurs as the economic structure shifts and older, polluting technologies are replaced with cleaner alternatives, a process referred to as the composition and technique effects [76].

The asymmetry in these relationships is theoretically grounded in the concept of irreversibility and hysteresis in environmental economics, where ecological damages from adverse shocks (e.g., heightened EPU or FDI outflows) are not easily reversible due to ecosystem thresholds, whereas beneficial shocks may yield diminishing returns [33]. This justifies the use of NARDL models to capture differential impacts of positive and negative changes in the independent variables on ecological footprint, extending prior linear approaches [71]. By integrating these theories, the study contributes to understanding how Saudi Arabia can navigate policy uncertainties and leverage natural resources and FDI for sustainable development, aligning with global agendas like the SDGs. Based on the above theoretical framework, this research has formulated the following hypothesis:

H1 EPU has an asymmetric impact on the ecological footprint in Saudi Arabia.

H2 Economic growth asymmetrically affects the ecological footprint in Saudi Arabia.

H3 FDI exerts an asymmetric effect on the ecological footprint in Saudi Arabia.

H4 NR asymmetrically influence the ecological footprint in Saudi Arabia.

2.2 Economic policy uncertainty and environmental quality

EPU has a complex and evolving relationship with environmental quality [69]. From a theoretical perspective, EPU is perceived to affect the environment indirectly through production and consumption mechanisms. Specifically, an increase in policy uncertainty can induce industries to rely on traditional, polluting manufacturing processes rather than cleaner production approaches, which are more susceptible to policy shocks [69]. Moreover, an increase in EPU may lead to a decline in research and development activities, resulting in reduced adoption of environmentally friendly technologies and cleaner, more efficient energy use, ultimately contributing to greater environmental degradation [14]. Unlike these prevailing assertions, some studies argue that EPU may also contribute to environmental sustainability. An upsurge in EPU can induce firms to delay large-scale investments, particularly in capital-intensive industries such as fossil fuel extraction, mining, and heavy manufacturing. These delays may temporarily reduce energy-intensive activities and, consequently, lower pollution levels [45].

Despite the extensive examination of the nexus between EPU and environmental quality, empirical research, much like the theoretical arguments, has reached no consensus. The available evidence varies considerably depending on the timeframe, data samples, and estimation techniques employed. For example, Huang et al. [39, 40] found that EPU significantly influences environmental quality across 19 advanced and emerging economies from 2001 to 2019. Similarly, Wang et al. [81] employed a GMM approach to assess the environmental impact of economic uncertainty in 137 countries from 1970 to 2018. Their results uncover that increased uncertainty contributes to higher pollution levels. Anser et al. [14] used a PMG-ARDL model to study the top ten carbon-emitting countries and found that EPU escalates CO_2 emissions. These findings align with other empirical studies, such as Adedoyin and Zakari [4] for the UK (1985–2017), and Adams et al. [2] for economies with high geopolitical risk between 1996 and 2017.

In contrast, some studies suggest that EPU may reduce environmental degradation. Ayhan et al. [19], using a quantile-on-quantile regression (QQR) method, examined the asymmetric impact of EPU and other variables on CO_2 emissions in G7 countries (1997–2021) and found that EPU reduces emissions. Zhengxia et al. [88] also reported that EPU improves environmental quality in China. Similar conclusions were drawn by Syed et al. [72] for BRICST countries (1990–2015), Chu and Le [25] for G7 nations (1997–2015), and Yang et al. [90] for 30 provinces in China (2008–2020). These contrasting findings highlight the nuanced and context-specific nature of the EPU-environment nexus.

2.3 Economic growth and environmental quality

The relationship between economic progress and environmental quality has long been a central concern in economics, environmental science, and policymaking circles [64].

This nexus reflects a complex and multidimensional interaction, shaped by both local conditions and global environmental challenges.

Empirical studies have examined the nexus between economic growth and the environment across different regions and at the country level using recent and sophisticated linear and nonlinear techniques of estimation. While their findings are significant, they remain inconclusive. For instance, Khan et al. [47] employed the GMM model for Belt and Road Initiative (BRI) economies over the period 2002–2019, finding that economic growth significantly contributes to environmental pollution in the region. Similarly, Abdul-Mumuni et al. [1] used a panel ARDL approach to assess the nonlinear impact of economic development on environmental degradation across 31 sub-Saharan African countries from 1990 to 2018. Their findings revealed that both positive and negative shocks in economic growth led to increased environmental degradation.

Liu et al. [50] analyzed the effects of economic growth, energy productivity, and globalization on CO_2 emissions in Southern European countries from 1990 to 2018. Their results confirmed that rising GDP intensifies environmental pollution in the region. Likewise, Adebayo [3] found that economic growth, alongside coal consumption and natural resource use, reduces environmental quality in China. In the South American context, Ali et al. [9, 10] concluded that declines in economic growth are associated with deteriorating environmental quality. These findings are consistent with a broad body of literature, including studies by Pan et al. [60] for Pakistan, Ahmad et al. [6] for G-11 countries, and Yang and Usman [89] for the top ten healthcare-expenditure economies, all of which report a negative environmental impact of economic expansion. Recently, using sectoral-level data, Bagci et al. [20] found that economic growth significantly contributes to rising carbon emissions in the agricultural sector. Furthermore, Destek et al. [31] applied a machine learning–based Kernel Regularized Least Squares technique to the longest available data interval (1945–2020) for the United States. The authors found that GDP growth has a discernible impact on emissions. Degirmenci & Aydin [30] emphasized that economic growth reduces environmental quality for a group of panel data.

2.4 Foreign investment and environmental quality

FDI has sparked a lively debate in the environmental sustainability discourse, especially in developing countries. On the one hand, a considerable number of analysts criticized FDI due to its contribution to environmental pollution. Empirical research on the impact of FDI on environmental quality has produced mixed findings, often influenced by the econometric methods used and the specific countries studied [68]. The environmental effects of FDI can be either positive or negative. For example, Wang et al. [82, 83] employed a dynamic ARDL model to examine the effects of foreign investment, financial development, urbanization, and innovation on CO_2 emissions in China from 1970 to 2021, finding that FDI improves environmental quality. Similarly, Saqib et al. [65] used the AMG approach to test the pollution halo hypothesis across 16 European countries (1990–2020), validating the pollution halo hypothesis in the region. Naseem et al. [57] analyzed the relationship between FDI and greenhouse gas emissions in the G-8 economies from 2000 to 2021 using DOLS, concluding that FDI reduces pollution levels. Xu et al. [87, 88], applying System-GMM, reported that foreign firms contribute to lower pollution levels in 48 Belt and Road Initiative economies. Similar studies include investigations by Uddin et al. [73] for BRICS, Ali et al. [9, 10] for Saudi Arabia, and Xu et al. [87, 88], for the E-7 economies.

In contrast, some studies find that FDI worsens environmental quality. Amoah et al. [12] found that FDI has a negative environmental impact in 30 Sub-Saharan African countries. Balsalobre-Lorente et al. [22] confirmed the pollution haven hypothesis in APEC countries. Ozturk et al. [59] also found that FDI increases pollution in South Asian economies. These contrasting results highlight the complex and context-dependent nature of the FDI-environment relationship.

2.5 Natural resources and environmental quality

Shedding light on the nexus between environmental quality and natural resources dependence, the available literature has yielded mixed results, highlighting the dual role these resources can play in either mitigating or exacerbating environmental degradation. For example, Jahanger et al. [43] investigated the effects of natural resources, globalization, and institutional quality on environmental outcomes in 73 emerging economies from 1990 to 2018, finding through panel threshold methods that natural resources negatively affect environmental quality. Similarly, Mehmood [53] found that reductions in natural resource use were associated with decreased environmental pollution. Zhou et al. [89] also reported that natural resources contributed to environmental improvement in Pakistan from 1980 to 2018. Supporting this positive perspective, studies by Dada et al. [28] for Nigeria, Ulucak et al. [77] for BRICS countries, and Zafar et al. [86] for the United States indicate that natural resources can enhance environmental quality.

On the other hand, some research shows that natural resource exploitation leads to increased pollution. Ahmad et al. [7], employing a CS-ARDL model, found that natural resources contribute to higher environmental pollution in developing economies. Ibrahim et al. [42] also used CS-ARDL methods to demonstrate that natural resource use reduces environmental quality in the top five carbon-emitting African countries. Furthermore, Jahanger et al. [44] revealed that natural resources intensify environmental contamination in BRICS nations. Likewise, Ullah et al. [75] utilized the ARDL approach to show that natural resource use increases pollution levels across 48 economies, including Turkey. These contrasting findings underscore the complex and context-specific relationship between natural resources and environmental sustainability.

3 Research gaps

Despite Saudi Arabia's prominence as a leading natural resource-driven economy, empirical evidence exploring the relationship between EPU and environmental quality within its unique socio-economic and geopolitical context remains scarce. This gap is particularly significant given the country's ambitious Vision 2030 agenda, which seeks to balance economic diversification with environmental sustainability, yet few studies have examined how EPU influences ecological outcomes in this setting.

Additionally, prior research has predominantly relied on CO_2 emissions as a proxy for environmental sustainability, which primarily captures air pollution and overlooks broader ecological impacts such as land use, water consumption, and biodiversity loss. The ecological footprint, a more comprehensive indicator, has been underutilized in the context of Saudi Arabia, limiting the understanding of the holistic environmental consequences of economic activities. Moreover, much of the existing literature employs linear estimation techniques, which fail to account for the asymmetric and nonlinear dynamics between EPU, economic growth, foreign direct investment, natural resources, and environmental outcomes.

Finally, most studies utilize the EPU index developed by Baker et al. [21], which focuses primarily on economic uncertainty and does not fully capture the interplay of political and economic uncertainties prevalent in Saudi Arabia's policy landscape. In contrast, the World Uncertainty Index (WUI) by Ahir et al. [5] integrates both dimensions, offering a more robust measure for analyzing uncertainty's impact on environmental performance. This study addresses these gaps by employing the NARDL model to investigate the asymmetric effects of EPU, GDP, FDI, and NR on the ecological footprint in Saudi Arabia, providing a nuanced contribution to the literature and informing targeted policy interventions.

4 Data and methodological strategy

4.1 Data

This study analyzes data for Saudi Arabia spanning 1995–2024. The dependent variable, environmental quality, is proxied by the ecological footprint, measured in global hectares per person (Gha/person) [35]. The primary independent variable is economic policy uncertainty (EPU), represented by the World Uncertainty Index (WUI) [86], which has been effectively applied to MENA countries [18]. The WUI is selected over the Baker et al. [21] EPU index due to its broader coverage of both economic and political uncertainty, which is particularly relevant for Saudi Arabia given its unique socio-political context and ongoing economic diversification under Vision 2030. Political uncertainty, such as shifts in governance or policy reforms, can influence environmental outcomes by affecting investor confidence and the prioritization of sustainable policies. For instance, heightened political uncertainty may deter long-term green investments while encouraging short-term resource exploitation, aligning with the Treadmill of Production Theory [66]. This dual capture of economic and political dimensions makes the WUI a more suitable measure for examining how uncertainty impacts ecological sustainability in Saudi Arabia's resource-driven economy.

The study also includes several control variables: economic growth (annual GDP growth rate, %), foreign direct investment (net inflows as a percentage of GDP), and natural resources (total natural resource rents as a percentage of GDP). Since the WUI data is available quarterly, the annual values used here are computed as the average of the four quarters for each year. Ecological footprint data is sourced from the Global Footprint Network [35], economic policy uncertainty data from the World Uncertainty Index (WUI, 20,225), and data for economic growth, foreign investment, and natural resources are obtained from the World Development Indicators [84]. Table 1 summarizes the variables along with their descriptions and data sources.

4.2 Econometric model and methodology

This study attempts to inspect the impact of EPU, GDP, FDI, and NR on EFP from 1995 to 2024. The functional form of this study can be discovered as follows in Eq. (1):

$$EPF_t = f\left(EPU_t, GDP_t, FDI_t, NR_t\right) \quad (1)$$

Table 1 Variables' description and sources

Abbreviation	Variable	Description	Source	Literature source
EFP	Ecological footprint	Gha per person	[35]	Saqib et al. [65]
EPU	Economic policy uncertainty	World Uncertainty Index	[86]	Ayad et al. [18]
GDP	Economic growth	GDP growth (annual %)	[84]	Farooq et al. [34]
FDI	Foreign direct investment	Foreign direct investment, net inflows (% of GDP)	[84]	Naseem et al. [57]
NR	Natural resources	Total natural resources rents (% of GDP)	[84]	Ullah et al. [75]

This study foresees a nonlinear model to scrutinize the asymmetric impacts of EPU, GDP, FDI, and NR on Saudi Arabian EFP. The impacts can be positive or negative shocks succeeding the concept of hidden cointegration established by Granger and Yoon [36]. Thus, to examine asymmetric effects, the study uses the NARDL method [71] by following Wang et al. [81]. Whereas the functional form of the nonlinear model through positive and negative shocks can be assumed as Eq. (2):

$$EFP_t = f\left\{(EPU)_t^+, (EPU)_t^-, (GDP)_t^+, (GDP)_t^-, (FDI)_t^+, (FDI)_t^-, (NR)_t^+, (NR)_t^-\right\} \tag{2}$$

In Eq. (2), the functional form specifies the asymmetric shocks in economic policy uncertainty $[(EPU)_t^+, (EPU)_t^-]$, economic growth $[(GDP)_t^+, (GDP)_t^-]$, foreign direct investment $[(FDI)_t^-, (NR)_t^+]$, and natural resources $[(NR)_t^+, (NR)_t^-]$ to asymmetrically affect the ecological footprint of Saudi Arabia. To avoid the chances of serial correlation, heteroscedasticity, and data spikiness, the study transforms the regressors into the logarithmic form. Equation (3) shows the transformation of regressors as follows:

$$\begin{aligned} lnEFP_t = \alpha_0 + \alpha_1 ln\,(EPU)_t^+ + \alpha_2\,(EPU)_t^- + \alpha_3\,(GDP)_t^+ + \alpha_4\,(GDP)_t^- \\ + \alpha_5\,(FDI)_t^+ + \alpha_6\,(FDI)_t^- + \alpha_7\,(NR)_t^+ + \alpha_8\,(NR)_t^- + \mu_t \end{aligned} \tag{3}$$

Before inspecting cointegration among the regressors, it is crucial to first create the integration procedure with empirical evidence of a unit root. This study uses the Augmented Dickey-Fuller (ADF) unit root test [32] to estimate the association of stationary variables.

To rule out the potential that merely one-order integration in a time series, the Phillips and Perron [62] unit root test is applied. ADF and PP stationarity tests do not allow structural breaks. Once the stationary alternative is countable and the structural break is discounted, the ability to reject a unit root is presented by Perron. Zivot and Andrews [90] introduced the Perron unit root test that reflects the endogenous breakpoint.

Primarily, the NARDL bound method assesses the cointegration amongst EFP, EPU, GDP, FDI, and NR for possible cointegration amongst indicators. Though Eq. (4) assumes the equation for estimation of cointegration as follows:

$$\begin{aligned}\Delta lnEFP_t = {} & \psi_0 + \psi_1 lnEFP_{t-1} + \psi_2 lnEPU^+_{t-1} + \psi_3 lnEPU^-_{t-1} + \psi_4 lnGDP^+_{t-1} \\ & + \psi_5 lnGDP^-_{t-1} + \psi_6 lnFDI^+_{t-1} + \psi_7 lnFDI^-_{t-1} + \psi_8 lnNR^+_{t-1} + \psi_9 lnNR^-_{t-1} \\ & + \sum_{i=1}^{k} \phi_1 \Delta lnEFP_{t-i} + \sum_{i=0}^{k} \phi_2 \Delta lnEPU^+_{t-i} + \sum_{i=0}^{k} \phi_3 \Delta lnEPU^-_{t-i} \\ & + \sum_{i=0}^{k} \phi_4 \Delta lnGDP^+_{t-i} + \sum_{i=0}^{k} \phi_5 \Delta lnGDP^-_{t-i} + \sum_{i=0}^{k} \phi_6 \Delta lnFDI^+_{t-i} \\ & + \sum_{i=0}^{k} \phi_7 \Delta lnFDI^-_{t-i} + \sum_{i=0}^{k} \phi_8 \Delta lnNR^+_{t-i} + \sum_{i=0}^{k} \phi_9 \Delta lnNR^-_{t-i} + \mu_t\end{aligned} \quad (4)$$

Equation (4) is associated with assessing the cointegration amongst EFP, EPU, GDP, FDI, and NR to confirm the prospect of long-run asymmetric effects. The NARDL bound approach is employed the positive–negative shocks of indicators, to specify the cointegration in circumstances of nonlinear. Though the cointegration amongst the indicators is feasible on the confirmation of both hypotheses (null and alternative hypotheses) based on F-statistics, critical values of the lower and upper bounds. Considering the condition, the value of the F-statistic greater than the bounds critical values supports to alternative hypothesis for the existence of cointegration, otherwise pointing toward acceptance of the null hypothesis that shows the non-existence of cointegration [61, 71]. Following both circumstances of null and alternative hypotheses are present as below:

Null hypothesis $(H_0) = \beta^+ = \beta^- = 0$ Alternative hypothesis $(H_1) \neq \beta^+ \neq \beta^- \neq 0$.

Once cointegration was confirmed, further analysis continued to estimate the asymmetric impacts in long and short periods. Hence, this study employs the NARDL technique introduced by Shin et al. [71] to detect the asymmetric effects, which are ignored by a simple linear method. This nonlinear ARDL approach is estimated to scrutinize the asymmetric impacts of EPU, GDP, FDI, and NR on EFP, throughout both shocks (positive and negative) in the short and long run, following Wang et al. [82, 83]. For the positive–negative effect of the estimated variables, parameters are displayed from Eq. (5) to Eq. (12) as follows:

$$lnEPU^+_t = \sum_{n=1}^{t} \Delta lnEPU^+_t = \sum_{n=1}^{t} max(\Delta lnEPU^+_t, 0) \quad (5)$$

$$lnEPU^-_t = \sum_{n=1}^{t} \Delta lnEPU^-_t = \sum_{n=1}^{t} min(\Delta lnEPU^-_t, 0) \quad (6)$$

$$lnGDP^+_t = \sum_{n=1}^{t} \Delta lnGDP^+_t = \sum_{n=1}^{t} max(\Delta lnGDP^+_t, 0) \quad (7)$$

$$lnGDP^-_t = \sum_{n=1}^{t} \Delta lnGDP^-_t = \sum_{n=1}^{t} min(\Delta lnGDP^-_t, 0) \quad (8)$$

$$lnFDI^+_t = \sum_{n=1}^{t} \Delta lnFDI^+_t = \sum_{n=1}^{t} max(\Delta lnFDI^+_t, 0) \quad (9)$$

$$lnFDI_t^- = \sum_{n=1}^{t} \Delta lnFDI_t^- = \sum_{n=1}^{t} min(\Delta lnFDI_t^-, 0) \quad (10)$$

$$lnNR_t^+ = \sum_{n=1}^{t} \Delta lnNR_t^+ = \sum_{n=1}^{t} max(\Delta lnNR_t^+, 0) \quad (11)$$

$$lnNR_t^- = \sum_{n=1}^{t} \Delta lnNR_t^- = \sum_{n=1}^{t} min(\Delta lnNR_t^-, 0) \quad (12)$$

Nevertheless, it is essential to estimate the short-run impacts, and this study expresses the short-run or error correction equation as below:

$$\begin{aligned}\Delta lnEFP_t = {} & \varphi_0 + \sum_{i=1}^{q} \varphi_1 \Delta lnEFP_{t-i} + \sum_{i=1}^{q} \varphi_2 \Delta lnEPU_{t-i}^+ + \sum_{i=1}^{q} \varphi_3 \Delta lnEPU_{t-i}^- \\ & + \sum_{i=1}^{q} \varphi_4 \Delta lnGDP_{t-i}^+ + \sum_{i=1}^{q} \varphi_5 \Delta lnGDP_{t-i}^- + \sum_{i=1}^{q} \varphi_6 \Delta lnFDI_{t-i}^+ + \sum_{i=1}^{q} \varphi_7 \Delta lnFDI_{t-i}^- \\ & + \sum_{i=1}^{q} \varphi_8 \Delta lnNR_{t-i}^+ + \sum_{i=1}^{q} \varphi_9 \Delta lnNR_{t-i}^- + \rho_1 lnEFP_{t-1} + \rho_2 lnEPU_{t-1}^+ \\ & + \rho_3 lnEPU_{t-1}^- + \rho_4 lnGDP_{t-1}^+ + \rho_5 lnGDP_{t-1}^- + \rho_6 lnFDI_{t-1}^+ \\ & + \rho_7 lnFDI_{t-1}^- + \rho_8 lnNR_{t-1}^+ + \rho_9 lnNR_{t-1}^- + \mu_t \end{aligned} \quad (13)$$

The above equation of the short-term asymmetric effect displays the short-term effects∋g asymmetry for the dynamic multiplier graphs, with long-period positive–negative variations in ecological footprint, is developed. The dynamic multiplier plots for EPU, GDP, FDI, and NR are derived after the positive and negative variations of the new equilibrium equation. Furthermore, all the analysis steps, which are used in this estimation displayed in the following Fig. 1.

5 Results and discussion

5.1 Descriptive statistics and correlation analysis

The discussion begins with a statistical overview, including descriptive statistics and correlation analysis. Table 2 presents the descriptive statistics, highlighting the variability of the key variables. All variables show variation around their means, as indicated by their standard deviations. Additionally, EFP, EPU, FDI, and NR exhibit negative skewness, whereas GDP shows positive skewness. In terms of kurtosis, EFP, GDP, and NR are platykurtic (flatter distributions), while EPU and FDI are leptokurtic (more peaked). The Jarque–Bera test and its corresponding p-values suggest that none of the variables (EFP, EPU, GDP, FDI, and NR) significantly deviate from normality, making them suitable for further nonlinear econometric analysis.

Following this, the correlation matrix (Table 3) reveals that EPU and GDP have correlation coefficients with EFP above the threshold value of 0.30, indicating a moderate correlation. Conversely, FDI and NR have correlations below 0.30 with EFP, implying a weak relationship. Overall, these statistical findings provide a sound foundation for subsequent empirical estimation as there are no multicollinearity[1] issues in this dataset.

[1] VIF values for LnEPU, LnGDP, LNFDI, and LnNR are 2.321, 3.012, 2.114, and 2.587.

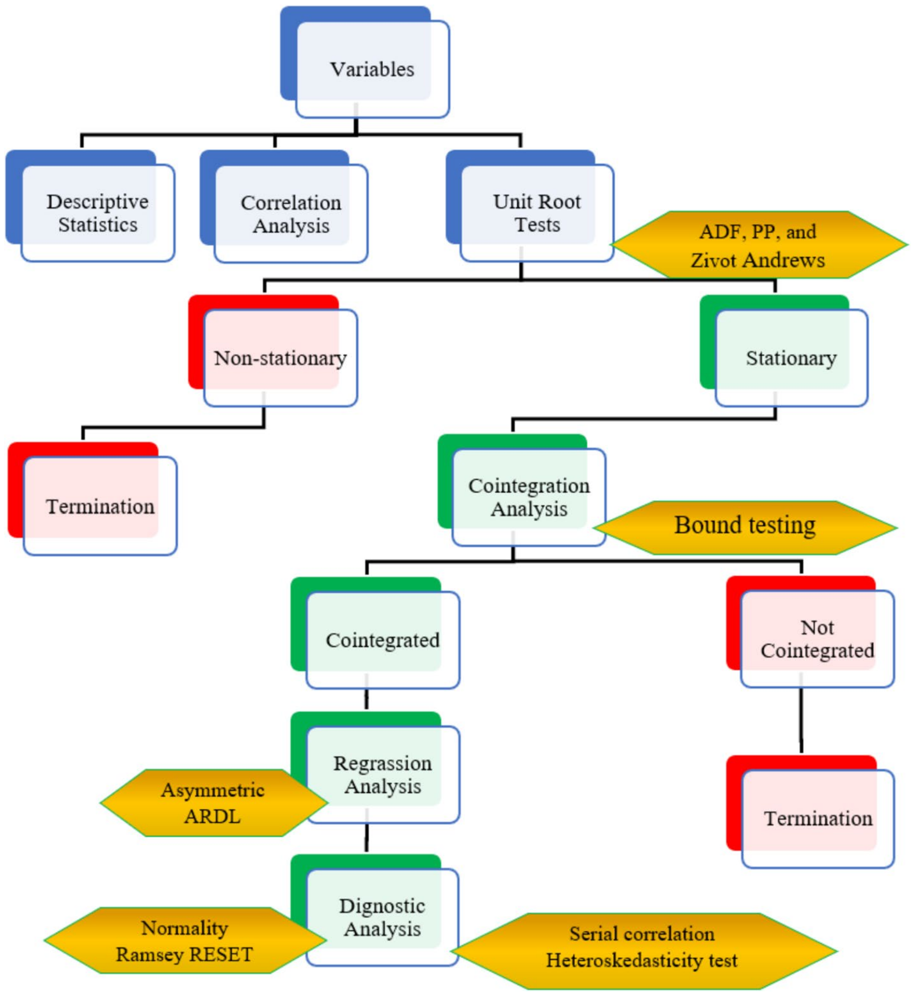

Fig. 1 Analysis flowchart

Table 2 Descriptive statistics

	LnEFP	LnEPU	LnGDP	LnFDI	LnNR
Mean	1.54328	−2.521638	26.92696	−0.125547	3.564197
Median	1.612544	−2.321811	26.89012	0.078273	3.560474
Maximum	1.93479	−1.402401	27.29797	2.159637	4.107777
Minimum	0.85782	−4.193587	26.54593	−4.540699	2.851771
Std. Dev	0.29580	0.721612	0.270738	1.622514	0.314712
Skewness	−0.79961	−0.863565	0.072837	−0.896211	−0.390409
Kurtosis	2.82831	3.370782	1.480092	3.625182	2.198196
Jarque–Bera	2.74748	3.380496	2.525620	3.903930	1.356947
Probability	0.26447	0.184474	0.282858	0.141995	0.507391
Sum	39.96593	−62.70258	699.5810	−2.744229	92.14911
Sum Sq. Dev	2.02835	13.01809	1.832476	65.81383	2.476094

5.2 BDS test results

This study also examines the linearity of the selected variables using the Brock-Dechert-Scheinkman (BDS) test, developed by Brock et al. (1996). The BDS test is a nonparametric method that does not require specifying the underlying data-generating process or higher-order moments, making it robust for detecting nonlinearity [51]. It tests whether

Table 3 Correlation analysis

Variables	LnEFP	LnEPU	LnGDP	LnFDI	LnNR
LnEFP	1.000000				
LnEPU	0.450628**	1.000000			
	(2.36747)	–			
LnGDP	0.786232***	0.375335**	1.000000		
	(9.46207)	(1.96765)	–		
LnFDI	0.153492**	−0.268863***	0.235138*	1.000000	
	(0.76646)	(−1.36751)	(1.17984)	–	
LnNR	0.061964*	−0.173316**	−0.187755	0.281470**	1.000000
	(0.29622)	(−0.86699)	(−0.96129)	(1.46147)	–

***indicates 1%, **shows 5%, and *presents a 10% significance level

Table 4 BDS test results

Series	LnEFP	LnEPU	LnGDP	LnFDI	LnNR
Dimensions	BDS Statistics				
2	0.1579***	−0.0116***	0.1885***	0.0684***	−0.0341***
3	0.2689***	−0.0240**	0.2849***	0.0731***	−0.0348***
4	0.2673***	−0.0410***	0.3744***	0.1230***	−0.0368***
5	0.3511***	−0.0439**	0.4168***	0.1284***	−0.0362**
6	0.3538***	−0.0093**	0.4374***	0.1514***	−0.1523***

***indicates 1% and **shows 5% significance level

Table 5 Results of unit root analysis

	First difference with constant				First difference with Trend		
Test	ADF		PP		Z-A's test (with SB)		
Series	t-stats	Prob	t-stats	Prob	t-stats	Prob	Breaks
LnEFP	−3.5576**	0.0154	−5.6390**	0.0241	−3.8083**	0.0148	2016
LnEPU	−4.8721***	0.0012	−7.3435***	0.0000	−5.8503**	0.0376	2008
LnGDP	−2.9079*	0.0630	−3.9743***	0.0058	−2.1439***	0.0007	2016
LnFDI	−3.0474**	0.0446	−3.0798**	0.0418	−3.3633***	0.0052	2010
LnNR	−4.8842***	0.0008	−4.1393***	0.0050	−3.4712**	0.0142	2009

***indicates 1%, **shows 5%, and *presents a 10% significance level

a time series is independently and identically distributed (i.i.d.) based on the correlation integral concept introduced by Grassberger and Procaccia [37]. The BDS test statistics are reported in Table 4, which indicates that the assumption of linearity is violated for all variables, confirming their nonlinear nature. Accordingly, this study adopts the NARDL approach to investigate the asymmetric effects of the regressors on Saudi Arabia's ecological footprint.

5.3 Unit root results

To assess the stationarity of the variables, this study employs several unit root tests, primarily the ADF and PP tests. The results of these conventional tests, presented in Table 5, show that all variables contain unit roots at their levels. However, after first differencing, EPU and NR become stationary at the 1% significance level, while EFP and FDI are stationary at the 5% level according to both tests. GDP is stationary at the 10% significance level in the ADF test and at 1% in the PP test.

Traditional unit root tests, however, often fail to account for structural breaks in the data, which are common in time series and can lead to misleading results if ignored. To address this, the Zivot–Andrews (Z–A) test, which allows for an endogenous structural break, is applied. Table 5 also shows the Z–A test outcomes, indicating that all variables are stationary after first differencing. The identified breakpoints correspond to events such as economic recessions, fluctuations in global oil demand, or geopolitical shocks. Based on these findings, the study concludes that the variables are suitable for cointegration analysis.

5.4 Nonlinear bounds cointegration

To examine the cointegrating relationship among the selected variables, this study applies the nonlinear bounds testing approach. Table 6 presents the results of the nonlinear bounds test for cointegration among EFP, EPU^+, EPU^-, GDP^+, GDP^-, FDI^+, FDI^-, NR^+, and NR^-. The estimated F-statistic value of 4.8462 is statistically significant at the 1% level and exceeds both the lower and upper critical bounds, confirming the existence of a long-run cointegrating relationship among the variables. The significance and magnitude of the F-statistic further justify the use of an asymmetric modeling framework. These findings suggest the need to evaluate the long- and short-run effects of both positive and negative shocks across the included variables.

5.5 NARDL long and short run results

The results of the nonlinear ARDL model are presented in Table 7, providing valuable insights into the asymmetric impact of EPU on Saudi Arabia's environmental quality, as proxied by the ecological footprint (EFP). The findings reveal that rising economic policy uncertainty has a complex and mixed effect on the environment.

Specifically, a 1% positive shock in EPU, representing a sharp increase in uncertainty, results in a 0.1847% rise in the EFP in the long run and a 0.0176% increase in the short run. This suggests that heightened uncertainty adversely impacts environmental quality, likely due to firms prioritizing cost-cutting production methods, reduced environmental compliance, and delays in green investments. During periods of elevated EPU, businesses and policymakers may defer environmentally sustainable actions, increasing the ecological burden. Conversely, a 1% negative shock in EPU, indicating reduced policy uncertainty, leads to a 0.1048% decrease in EFP in the long run, reflecting improved environmental outcomes driven by stable policy environments that encourage sustainable investments and regulatory adherence. However, in the short run, this negative EPU shock results in a 0.1051% increase in EFP, a divergence that can be attributed to a temporary surge in industrial and investment activities spurred by renewed policy confidence. This short-term increase likely stems from accelerated economic activity, such as expanded resource extraction or industrial output, which temporarily elevates

Table 6 NARDL bounds cointegration results

Test statistics	Value	K
F-statistic [EFP = f(EPU^+, EPU^-, GDP^+, GDP^-, FDI^+, FDI^-, NR^+, NR^-)]	4.8462***	8
Critical Value Bounds		
Significance	I (0) Bound	I (1) Bound
10%	1.85	2.85
5%	2.11	3.15
2.5%	2.33	3.42
1%	2.62	3.77

***indicates significance level at 1%

Table 7 Nonlinear ARDL Bound testing results [NARDL (1, 1, 1, 1, 1, 1, 1, 1, 1)]

Variable	Coefficient	Std. Error	t-Statistic	Prob
Long-run coefficients				
LnEPU_POS	0.1847***	0.0179	10.3184	0.0001
LnEPU_NEG	−0.1048***	0.0198	−5.2929	0.0000
LnGDP_POS	0.7896***	0.1410	5.6000	0.0000
LnGDP_NEG	0.4124***	0.1363	3.0256	0.0000
LnFDI_POS	−0.4501**	0.1872	−2.4043	0.0530
LnFDI_NEG	−0.2155***	0.0152	−14.1776	0.0000
LnNR_POS	−0.0124***	0.0041	−3.0244	0.0005
LnNR_NEG	0.0272***	0.0012	22.6667	0.0000
C	1.2173***	0.0229	53.0181	0.0000
Short-run coefficients				
D(LnEPU_POS)	0.0176	0.0237	0.7480	0.4827
D(LnEPU_NEG)	0.1051***	0.0330	3.1848	0.0016
D(LnGDP_POS)	−0.0513***	0.0048	−10.6875	0.0000
D(LnGDP_NEG)	0.0401***	0.0063	6.3492	0.0000
D(LnFDI_POS)	0.0230	0.0208	1.1004	0.3133
D(LnFDI_NEG)	−0.0277**	0.0199	−1.3908	0.0137
D(LnNR_POS)	−0.0361**	0.1596	−0.2258	0.0288
D(LnNR_NEG)	−0.1289	0.0665	−1.9369	0.1009
ECT (−1) *	−0.8564***	0.2156	−3.9722	0.0000

***indicates 1% and **shows 5% significance level

The optimal lag length was determined using the Akaike Information Criterion

environmental pressure before long-term sustainability measures take effect. The asymmetric and nonlinear framework of the NARDL model effectively captures these divergent dynamics, highlighting the time-varying impact of EPU shocks. These findings align with Assamoi and Wang [15], who observed similar short- and long-run dynamics in China and the United States, and Adams et al. [2], who noted comparable patterns in resource-rich economies.

In the long run, both positive and negative shocks to GDP are found to increase the EFP. Specifically, a 1% positive shock in GDP, representing economic expansion, raises the EFP by 0.7896%. This suggests that long-term economic growth in Saudi Arabia leads to increased environmental degradation, likely due to higher energy consumption, intensified industrial activity, infrastructure expansion, and greater demand for natural resources. Such a result aligns with the EKC literature that highlights how early stages of economic growth often come at the cost of environmental quality [13, 55]. Interestingly, a 1% negative shock in GDP, indicating economic contraction, also leads to a 0.4142% increase in EFP in the long run. This counterintuitive result may reflect structural inefficiencies in the Saudi economy, where downturns could reduce investments in environmental protection, delay sustainable development projects, or shift focus toward high-emission industries to recover growth. This finding suggests that economic decline does not necessarily lead to environmental relief in the Saudi context.

In the short run, the results reveal an asymmetric relationship between GDP shocks and the EFP. A 1% positive shock in GDP reduces EFP by 0.0513%, suggesting that short-term economic growth may enhance environmental efficiency. This effect can be attributed to targeted policy measures under Saudi Arabia's Vision 2030, which emphasize investments in cleaner technologies and stricter environmental regulations. For instance, initiatives like the Saudi Green Initiative promote renewable energy adoption and energy-efficient practices, which likely contribute to reduced ecological pressure during periods of economic expansion. Supporting evidence from Alzahrany et al. [11] highlights that recent investments in solar and wind energy projects in Saudi Arabia have improved resource efficiency, aligning with these findings. Conversely, a 1% negative GDP shock increases EFP by 0.0401%, indicating that economic downturns exacerbate environmental degradation, possibly due to relaxed regulatory enforcement or reliance on cheaper, pollution-intensive production methods during economic stress. In the long run, however, positive GDP shocks tend to increase EFP, reflecting the environmental cost of sustained economic expansion driven by resource-intensive industries. These nonlinear and asymmetric dynamics underscore the complex growth-environment nexus in Saudi Arabia. While short-term growth, supported by policy-driven technological advancements, may yield environmental benefits, negative GDP shocks consistently worsen ecological outcomes across both time frames. These findings emphasize the need for resilient economic strategies that integrate sustainable practices to mitigate environmental degradation, regardless of economic cycles.

Saudi Arabia is strategically positioning itself to become a global hub for FDI as part of its Vision 2030 development plan. However, the FDI inflow may have detrimental effects on the environment. Table 7 also presents the empirical findings regarding the relationship between FDI and Saudi Arabia's EFP. The results indicate that foreign investment plays a constructive role in improving environmental quality in the long run. Specifically, a 1% positive shock in FDI leads to a 0.4501% reduction in the EFP, suggesting that increased FDI inflows may be linked to the transfer of cleaner technologies, better environmental standards, and more efficient production practices. This supports the "pollution halo" hypothesis, which argues that foreign firms often bring advanced, environmentally friendly technologies and management practices to host countries.

In the short run, however, the effect of a positive FDI shock on the EFP is statistically insignificant. This might reflect the time lag between investment inflows and their environmental impact, as many green technologies or sustainability projects require long-term planning and implementation. On the other hand, a 1% negative shock in FDI, indicating a reduction in foreign investment, leads to a 0.2155% increase in environmental quality in the long term and a smaller 0.0277% improvement in the short term. These counterintuitive results may imply that when foreign investment declines, domestic industries potentially scale down production, thereby temporarily reducing resource consumption and emissions. However, such environmental gains may not be sustainable or intentional and may come at the cost of economic development. Overall, the findings highlight the nuanced and asymmetric role of FDI in shaping environmental outcomes in Saudi Arabia. The long-run benefits of increased FDI affirm that fostering an investment-friendly climate—particularly one that emphasizes green innovation and environmental governance—can support the Kingdom's efforts to balance economic growth with ecological sustainability. These results are in line with previous studies such as Saqib et al. [65] and Ali et al. (2023b, a), who also observed that FDI contributes positively to environmental performance in various regional and national contexts.

For a resource-rich country like Saudi Arabia, where oil and mineral extraction play a central role in the economy, assessing the environmental implications of natural resource utilization is especially critical. In the long run, the findings reveal that a 1% positive shock in natural resources, indicating increased resource availability or utilization, leads to a modest 0.0124% improvement in environmental quality. This suggests that resource wealth, when managed responsibly, may contribute positively to sustainability, potentially through reinvestment in cleaner technologies, diversification efforts, or environmental restoration programs. Conversely, a 1% negative shock in natural resources results in a 0.0272% increase in the EFP, signifying a deterioration in environmental quality. This may reflect disruptions in resource revenue or production that force a reliance on more environmentally damaging alternatives or reduce environmental oversight during economic stress.

In the short term, the results present a different picture. The coefficient for NR^+ is statistically significant at the 5% level, indicating that a short-term positive shock in resource utilization leads to a 0.0361% increase in the EFP, implying short-run environmental degradation despite long-run improvements. This may be due to the immediate environmental costs associated with resource extraction activities such as oil drilling or mining, which can generate pollution and land degradation before any offsetting sustainability measures take effect. Meanwhile, the NR^- coefficient is statistically insignificant in the short run, suggesting that reductions in resource extraction or availability do not have a meaningful immediate effect on environmental quality. This could be because the short-run environmental response to declining resource use is muted, or because other compensatory factors—such as increased industrial emissions from alternative sectors—counteract any immediate environmental gains. These asymmetric and time-dependent dynamics underscore the complexity of the resource-environment nexus in Saudi Arabia. While natural resource endowments can be leveraged to support long-term sustainability, they also pose risks when poorly managed or subject to economic volatility. The findings are consistent with prior studies such as Mehmood [53] and Ulucak et al. [77], which also observed mixed and context-specific outcomes regarding natural resource exploitation and environmental impacts.

Moreover, the error correction term (ECT_{t-1}) has a coefficient of − 0.8564, which is negative and statistically significant at the 1% level. This indicates a strong adjustment speed toward long-run equilibrium, with approximately 86% of any short-term deviation from the long-run relationship being corrected within one period. Such a high magnitude reflects a robust level of stability in the model. Additionally, the actual, estimated, and fitted values of the dependent variable, ecological footprint, over the long term are illustrated in Fig. 2, further confirming the model's goodness of fit and explanatory power.

5.6 Diagnostic test results

To ensure the robustness, reliability, and correct specification of the estimated model, several diagnostic tests were conducted in this study. These tests confirm that the model performs well in terms of statistical adequacy and methodological soundness. Table 8 summarizes the results of the diagnostic tests. The ARCH χ^2 and Breusch–Pagan–Godfrey heteroskedasticity tests indicate that the model does not suffer from heteroskedasticity, affirming homoscedastic error variance. Additionally, both the Durbin-Watson statistic and the Breusch-Godfrey LM test reveal no evidence of serial correlation, suggesting that the residuals are independently distributed. The Ramsey RESET test results further confirm that the model is correctly specified, with no indication of omitted variable bias. Moreover, the structural stability of the model is assessed using the

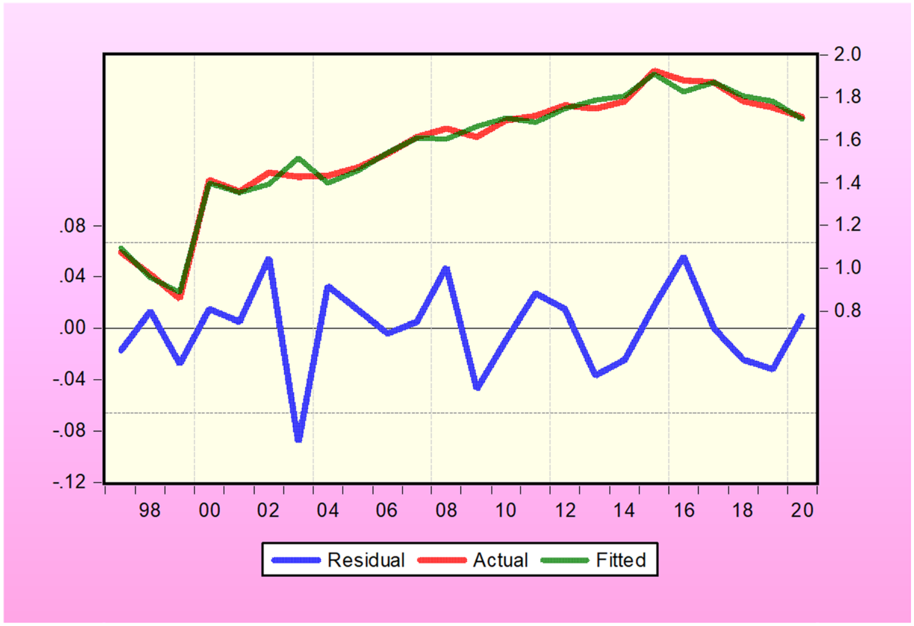

Fig. 2 Actual, estimated, and fitted terms of the EFP function

Table 8 Diagnostic analysis

Tests	F-statistic	Prob
Breusch-Godfrey LM test for serial correlation	1.5321	0.2983
Breusch-Pagan-Godfrey test for heteroskedasticity	0.8635	0.6421
ARCH test for heteroskedasticity	0.6983	0.4321
Jarque–Bera test for normality	1.1091	0.5931
Model Specification test: Ramsey RESET	3.0921	0.2391
Durbin-Watson stat	2.0053	

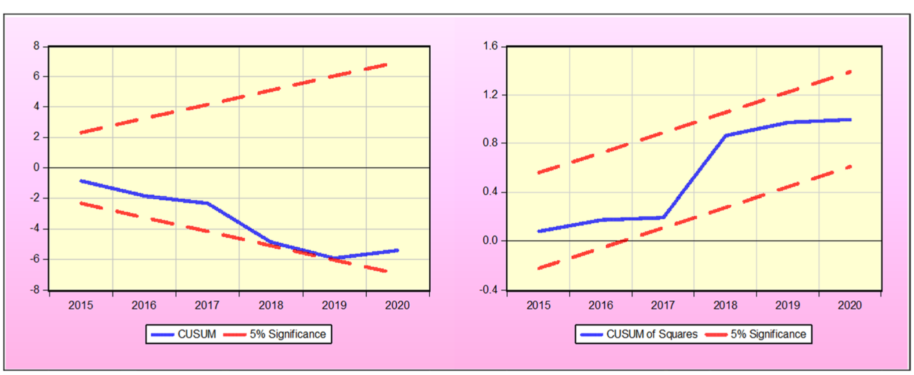

Fig. 3 NARDL-CUSUM and CUSUM Squares graphs

NARDL-based CUSUM and CUSUMSQ tests. As illustrated in Fig. 3, the plotted lines (blue) lie entirely within the 95% confidence bounds (red dotted lines), verifying that the model remains stable throughout the sample period.

Additionally, this study assessed the presence of long-run asymmetries by applying the Wald test, aiming to uncover the nonlinear behavior of the examined variables. The results, presented in Table 9, confirm the existence of significant asymmetries for all variables: EPU^{+}, EPU^{-}, GDP^{+}, GDP^{-}, FDI^{+}, FDI^{-}, NR^{+}, and NR^{-}. These findings indicate

Table 9 Wald Test results

Variables	F-statistic	Prob	Decision
LnEPU	0.0177**	0.0148	Yes
LnGDP	0.0775***	0.0065	Yes
LnFDI	0.1251**	0.0156	Yes
LnNR	0.0040**	0.0100	Yes

***indicates 1% and **shows 5% significance level

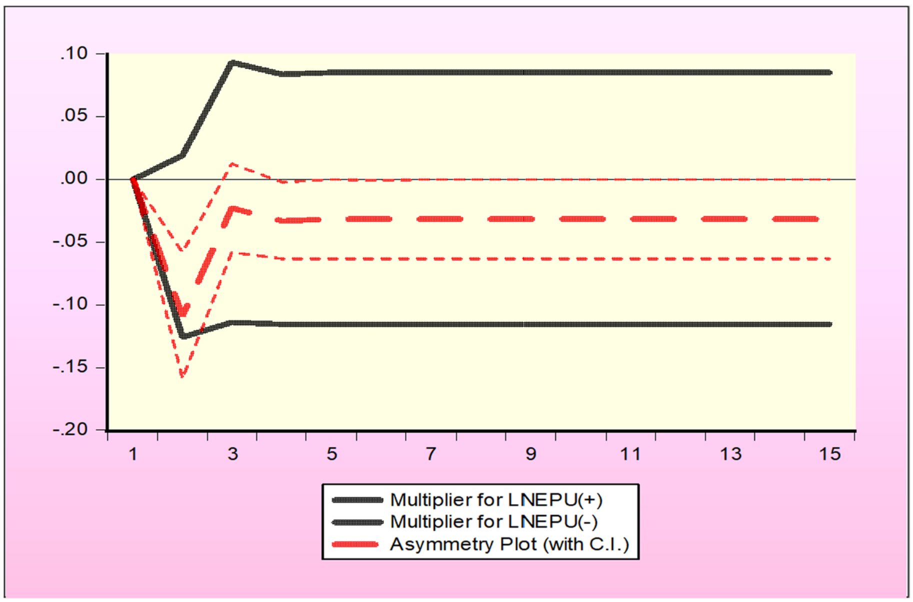

Fig. 4 LnEPU dynamic multiplier graph

that positive and negative shocks exert differing effects on the ecological footprint, either through changes in the magnitude of coefficients or through opposite directional impacts. The significance of these asymmetric relationships underscores the suitability and strength of using a nonlinear model such as the NARDL framework. The Wald test results further validate the robustness of the empirical analysis and confirm that accounting for asymmetry is both methodologically appropriate and necessary for drawing meaningful policy conclusions.

Lastly, this study investigates the dynamic adjustment path of the ecological footprint (EFP) in response to positive and negative shocks through the estimation of dynamic multipliers. The results are illustrated in Figs. 4, 5, 6 and 7. These figures depict how EFP gradually converges to its long-run equilibrium following asymmetric shocks in EPU, GDP, FDI, and natural resources (NR).

The dynamic multiplier plots clearly highlight the asymmetric behavior of the variables. Specifically, positive shocks in GDP and FDI have a more pronounced and persistent impact on increasing EFP compared to their negative counterparts, suggesting that expansions in economic activity and investment exert stronger environmental pressures than contractions alleviate. In contrast, negative shocks in EPU and NR demonstrate greater influence than positive shocks, indicating that increased uncertainty and resource depletion have more substantial environmental consequences than improvements in these areas.

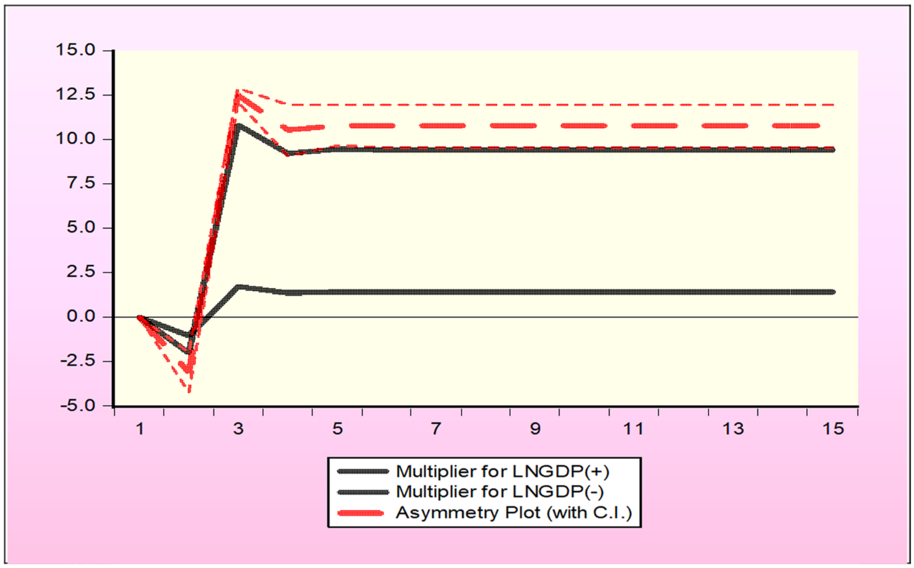

Fig. 5 LnGDP dynamic multiplier graph

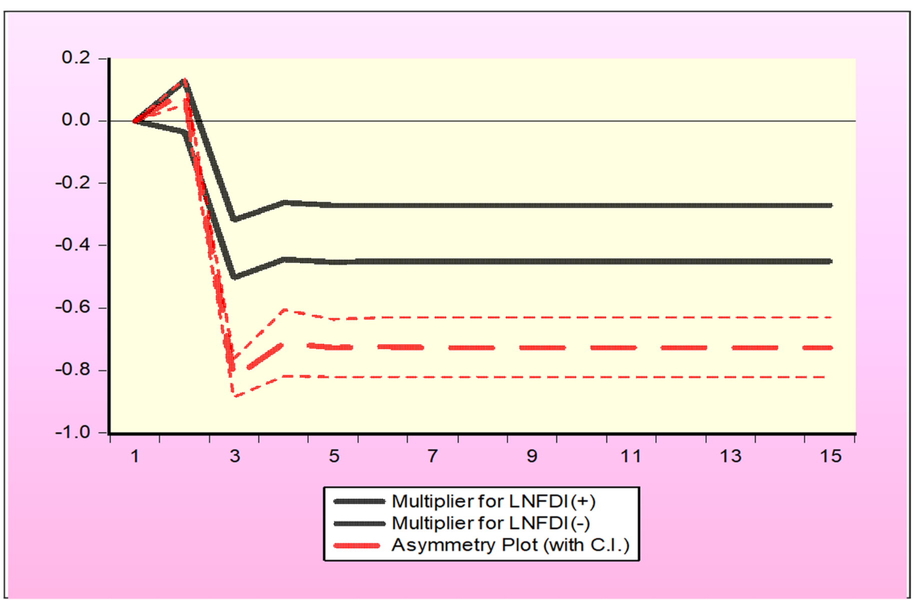

Fig. 6 LnFDI dynamic multiplier graph

These asymmetries further reinforce the need for nuanced, direction-sensitive policy responses aimed at mitigating environmental impacts, especially in the context of economic volatility and natural resource management.

6 Conclusion and policy implications

6.1 Conclusion

This study investigates the asymmetric effects of EPU, economic growth, FDI, and natural resource abundance on environmental quality in Saudi Arabia over the period 1995 to 2022. Prior to conducting the empirical analysis, the study examines the data characteristics. The results of these preliminary assessments confirm that the data are appropriate for further econometric modeling. To test for stationarity, the study applies

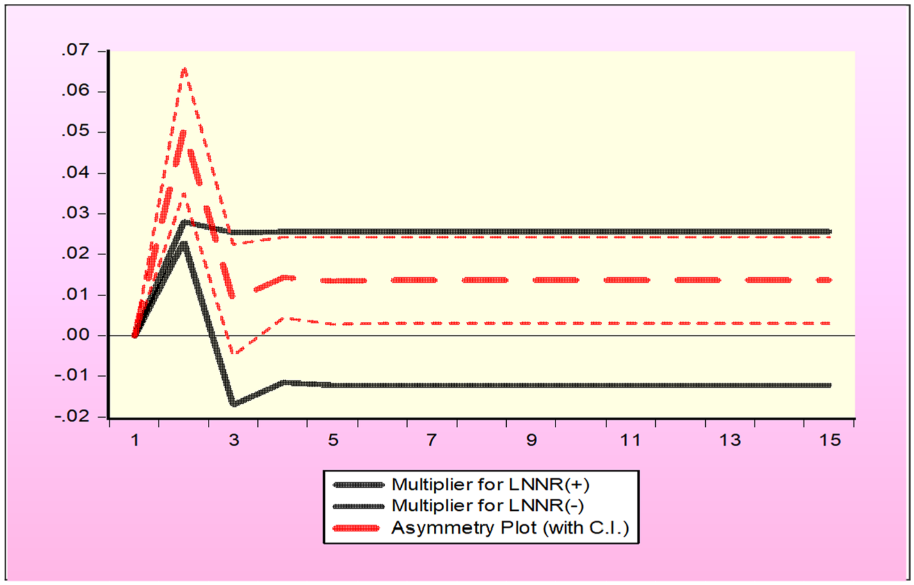

Fig. 7 LnNR dynamic multiplier graph

multiple unit root tests, including the ADF, PP, and Zivot–Andrews (ZA) tests. The findings reveal that all variables are stationary after first differencing. Given this, the study employs the NARDL bounds testing approach, which confirms the existence of a long-run cointegration relationship among the variables.

The results of the NARDL analysis reveal that rising EPU contributes negatively to environmental sustainability by increasing the ecological footprint (EFP) in the long run. Both positive and negative shocks to EPU are associated with a higher EFP in the short run, indicating that uncertainty has a detrimental impact on environmental quality. Regarding economic growth, the findings show that positive and negative shocks to GDP result in increased environmental degradation in the long run, while positive shocks are associated with reductions in the EFP in the short run. FDI, on the other hand, consistently shows a beneficial long-run impact on environmental quality. Both positive and negative FDI shocks lead to reduced EFP in the long term. However, in the short run, a negative shock in FDI slightly decreases the EFP. In the case of natural resources, a positive shock contributes to environmental improvement.

6.2 Policy implications

The findings of this study offer several policy implications tailored to Saudi Arabia's current economic landscape and its commitment to Vision 2030. First, the results highlight that positive shocks in EPU exacerbate environmental degradation by increasing the ecological footprint. To mitigate this, Saudi policymakers should prioritize stable, transparent, and predictable economic and environmental policies. In the context of Saudi Arabia's ongoing economic diversification efforts, reducing policy volatility through consistent regulatory frameworks and clear communication can bolster investor confidence and encourage long-term investments in sustainable infrastructure, such as renewable energy projects under the Saudi Green Initiative. International commitments, such as those aligned with the Paris Agreement, can further reinforce policy credibility and environmental accountability.

Second, the study reveals that positive GDP shocks reduce EFP in the short run but increase it in the long run, reflecting the environmental cost of sustained economic growth in a resource-dependent economy. Given Saudi Arabia's push for economic diversification in 2025, policymakers should integrate green growth strategies into the national development agenda. This includes scaling up investments in energy-efficient technologies, enforcing stringent environmental regulations, and expanding renewable energy capacity, such as solar and wind projects, which have already shown promise in reducing ecological pressure. These measures align with Vision 2030's goal of balancing economic growth with environmental sustainability while addressing SDG 13 on climate action.

Third, the positive long-run impact of FDI on environmental quality underscores the potential of FDI to drive sustainable development. However, negative FDI shocks were found to improve EFP, suggesting that unrestricted FDI inflows in high-emission sectors could counteract environmental gains. In light of Saudi Arabia's efforts to attract global investment in 2025, policymakers should strategically channel FDI into environmentally sustainable sectors, such as clean technology, green manufacturing, and circular economy initiatives, while tightening oversight of pollution-intensive industries. Incentives like tax breaks for green investments and adherence to global environmental standards can ensure that FDI supports Saudi Arabia's sustainability objectives without compromising economic growth.

Finally, the asymmetric effects of natural resource rents indicate that positive shocks improve environmental quality, while negative shocks exacerbate degradation. As Saudi Arabia remains heavily reliant on oil revenues in 2025, policymakers should accelerate diversification efforts to reduce dependence on resource extraction. Investments in sustainable resource management, such as carbon capture and storage technologies, and policies promoting resource efficiency, can mitigate the environmental impact of natural resource exploitation. By aligning these strategies with Vision 2030, Saudi Arabia can achieve a balance between leveraging its natural wealth and advancing ecological sustainability.

6.3 Limitations of this research

This study has several limitations that warrant consideration. The analysis is constrained by a relatively small sample size, spanning 1995–2024, which may limit the statistical power and generalizability of the findings. Additionally, the period includes potential structural breaks, notably the introduction of Saudi Arabia's Vision 2030 in 2016, which initiated significant economic and environmental policy reforms. These structural shifts may introduce instability in the relationships between economic policy uncertainty, economic growth, foreign direct investment, natural resources, and the ecological footprint, potentially affecting the robustness of the results. Data quality issues, such as inconsistencies in ecological footprint measurements or the World Uncertainty Index's aggregation of economic and political uncertainty, may further influence the precision of the estimates. The potential effects of converting the WUI index from quarterly to annual data using averages may smooth short-term fluctuations and reduce variability.

To address these limitations, future research could incorporate more recent data as they become available to extend the time series and enhance reliability. Moreover, employing advanced methodologies, such as quantile regression, could capture the heterogeneous and asymmetric impacts of these variables across different ecological and economic conditions. Including interaction terms in the model could also provide deeper insights into the complex interplay of these factors. By addressing these limitations, future studies can refine empirical evaluations and inform targeted policies to promote environmental sustainability in Saudi Arabia.

Acknowledgements
None.

Author contributions
Conceptualization, M.H., and M.E.H.; methodology, M.S., and M.E.H.; software, M.H.; validation, M.E.H.; formal analysis, M.H.; investigation, M.M.J.; resources, M.M.J.; data curation, S.M.; writing—original draft preparation, M.H., M.S., M.E.H., M.M.J., and S.M.; writing—review and editing, M.A.; visualization, M.A.; funding acquisition, M.A. All authors have read and agreed to the published version of the manuscript.

Funding
No funding applicable.

Data availability
Data used in this study is publicly available and can be found by browsing the website mentioned in the data source of the manuscript. Moreover, the datasets analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]School of Economics and Management, Wuhan University, Wuhan 430072, China
[2]Department of Management Studies, Graphic Era Deemed to be University, Dehradun, Uttarakhand 248002, India
[3]Advanced Research Centre, European University of Lefke, TR-10 Mersin, Lefke, Northern Cyprus, Turkey
[4]Applied Science Research Center, Applied Science Private University, Amman, Jordan
[5]Department of Political Science, Texas State University, San Marcos, Texas 78666, USA
[6]Department of Finance and Tourism, Termez University of Economics and Service, Termez, Uzbekistan
[7]Department of Economics, Mamun University, 220900 Khiva, Uzbekistan
[8]Departament of Finance, Alfraganus University, Tashkent, Uzbekistan
[9]Department of Economics, Faculty of Economics and Administrative Sciences, Balikesir University, Balikesir, Turkey
[10]Department of Applied Economics, Faculty of Economics, Social and Environmental Studies, University of Medical Sciences and Technology, Khartoum, Sudan

Received: 4 July 2025 / Accepted: 9 December 2025

Published online: 10 February 2026

References

1. Abdul-Mumuni A, Mensah BD, Amankwa Fosu R. Asymmetric effect of renewable energy consumption and economic growth on environmental degradation in sub-Saharan Africa. Int J Energy Sect Manag. 2023;17(5):1013–33. https://doi.org/10.1108/IJESM-07-2022-0009.
2. Adams S, Adedoyin F, Olaniran E, Bekun FV. Energy consumption, economic policy uncertainty and carbon emissions; causality evidence from resource rich economies. Econ Anal Policy. 2020;68:179–90. https://doi.org/10.1016/j.eap.2020.09.012.
3. Adebayo TS. Trade-off between environmental sustainability and economic growth through coal consumption and natural resources exploitation in China: new policy insights from wavelet local multiple correlation. Geol J. 2023;58(4):1384–400. https://doi.org/10.1002/gj.4664.
4. Adedoyin FF, Zakari A. Energy consumption, economic expansion, and CO2 emission in the UK: the role of economic policy uncertainty. Sci Total Environ. 2020;738:140014. https://doi.org/10.1016/j.scitotenv.2020.140014.
5. Ahir H, Bloom N, Furceri D (2022) The world uncertainty index (No. w29763). National bureau of economic research. https://www.nber.org/papers/w29763.
6. Ahmad M, Dai J, Mehmood U, Abou Houran M. Renewable energy transition, resource richness, economic growth, and environmental quality: assessing the role of financial globalization. Renew Energy. 2023;216:119000. https://doi.org/10.1016/j.renene.2023.119000.
7. Ahmad M, Jiang P, Majeed A, Umar M, Khan Z, Muhammad S. The dynamic impact of natural resources, technological innovations and economic growth on ecological footprint: an advanced panel data estimation. Resour Policy. 2020;69:101817. https://doi.org/10.1016/j.resourpol.2020.101817.
8. Ahmed Z, Asghar MM, Malik MN, Nawaz K. Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. Resour Policy. 2020;67:101677. https://doi.org/10.1016/j.resourpol.2020.101677.

9. Ali EB, Shayanmehr S, Radmehr R, Amfo B, Awuni JA, Gyamfi BA, et al. Exploring the impact of economic growth on environmental pollution in South American countries: how does renewable energy and globalization matter? Environ Sci Pollut Res Int. 2023;30(6):15505–22. https://doi.org/10.1007/s11356-022-23177-4.
10. Ali U, Guo Q, Nurgazina Z, Sharif A, Kartal MT, Depren SK, et al. Heterogeneous impact of industrialization, foreign direct investments, and technological innovation on carbon emissions intensity: evidence from Kingdom of Saudi Arabia. Appl Energy. 2023;336:120804. https://doi.org/10.1016/j.apenergy.2023.120804.
11. Alzahrany A, Kabir G, Al Zohbi G. Evaluation of the barriers to and drivers of the implementation of solar energy in Saudi Arabia. Int J Sust Dev World. 2022;29(6):543–58.
12. Amoah JO, Alagidede IP, Sare YA. Impact of foreign direct investment on carbon emission in Sub-Saharan Africa: the mediating and moderating roles of industrialization and trade openness. Cogent Bus Manag. 2023;10(3):2266168. https://doi.org/10.1080/23311975.2023.2266168.
13. Ansari MA, Ahmad MR, Siddique S, Mansoor K. An environment Kuznets curve for ecological footprint: evidence from GCC countries. Carbon Manag. 2020;11(4):355–68. https://doi.org/10.1080/17583004.2020.1790242.
14. Anser MK, Apergis N, Syed QR. Impact of economic policy uncertainty on CO2 emissions: evidence from top ten carbon emitter countries. Environ Sci Pollut Res Int. 2021;28:29369–78. https://doi.org/10.1007/s11356-021-12782-4.
15. Assamoi GR, Wang S. Asymmetric effects of economic policy uncertainty and environmental policy stringency on environmental quality: evidence from China and the United States. Environ Sci Pollut Res Int. 2023;30(11):29996–30016. https://doi.org/10.1007/s11356-022-24082-6.
16. Auty RM. Sustaining development in mineral economies: The resource curse thesis. Singapore: Routledge; 1993.
17. Ayad H, Haseeb M, Djedaiet A, Hossain ME, Kamal M. Investigating the nexus between trade policy uncertainty and environmental quality in the USA: empirical evidence from aggregate and disaggregate level analysis. Environ Sci Pollut Res Int. 2023;30(18):51995–2012. https://doi.org/10.1007/s11356-023-26026-0.
18. Ayad H, Sari-Hassoun SE, Usman M, Ahmad P. The impact of economic uncertainty, economic growth and energy consumption on environmental degradation in MENA countries: fresh insights from multiple thresholds NARDL approach. Environ Sci Pollut Res Int. 2023;30(1):1806–24. https://doi.org/10.1007/s11356-022-22256-w.
19. Ayhan F, Kartal MT, Kılıç Depren S, Depren Ö. Asymmetric effect of economic policy uncertainty, political stability, energy consumption, and economic growth on CO2 emissions: evidence from G-7 countries. Environ Sci Pollut Res Int. 2023;30(16):47422–37. https://doi.org/10.1007/s11356-023-25665-7.
20. Bagci A, Sogut Y, Bozatli O, Degirmenci T. Policy support and agricultural greenhouse gas emissions in BRICS-T countries: the role of financial development, markets, and institutions. Borsa Istanbul Rev. 2025;25(5):886–94. https://doi.org/10.1016/j.bir.2025.05.004.
21. Baker SR, Bloom N, Davis SJ. Measuring economic policy uncertainty. Q J Econ. 2016;131(4):1593–636. https://doi.org/10.1093/qje/qjw024.
22. Balsalobre-Lorente D, Topaloglu EE, Nur T, Evcimen C. Exploring the linkage between financial development and ecological footprint in APEC countries: a novel view under corruption perception and environmental policy stringency. J Clean Prod. 2023. https://doi.org/10.1016/j.jclepro.2023.137686.
23. Batool Z, Raza SMF, Ali S, Abidin SZU. ICT, renewable energy, financial development, and CO2 emissions in developing countries of East and South Asia. Environ Sci Pollut Res. 2022;29(23):35025–35. https://doi.org/10.1007/s11356-022-18664-7.
24. Chu LK, Le NTM. Environmental quality and the role of economic policy uncertainty, economic complexity, renewable energy, and energy intensity: the case of G7 countries. Environ Sci Pollut Res. 2022;29(2):2866–82. https://doi.org/10.1007/s11356-021-15666-9.
25. Copeland BR, Taylor MS. North-South trade and the environment. Q J Econ. 1994;109(3):755–87. https://doi.org/10.2307/2118421.
26. Dada JT, Adeiza A, Noor AI, Marina A. Investigating the link between economic growth, financial development, urbanization, natural resources, human capital, trade openness and ecological footprint: evidence from Nigeria. J Bioeconom. 2022. https://doi.org/10.1007/s10818-021-09323-x.
27. Danish U, Khan SUD. Relationship between energy intensity and CO2 emissions: does economic policy matter? Sustain Dev. 2020;28(5):1457–64. https://doi.org/10.1002/sd.2098.
28. Degirmenci T, Aydin M. A path towards the sustainable environment from environmental governance: testing the LCC and EKC hypotheses with the environmental policy stringency and government effectiveness in France. J Knowl Econ. 2025. https://doi.org/10.1007/s13132-025-02665-1.
29. Destek MA, Degirmenci T, Kocak E. How does bank loans affect carbon emissions? A comparison of household and business loans. Environ Dev Sustain. 2025. https://doi.org/10.1007/s10668-025-06232-1.
30. Dickey DA, Fuller WA. Distribution of the estimators for autoregressive time series with a unit root. J Am Stat Assoc. 1979;74(366a):427–31. https://doi.org/10.1080/01621459.1979.10482531.
31. Dixit AK, Pindyck RS. Investment under uncertainty. Princeton University Press; 1994.
32. Farooq U, Tabash MI, Anagreh S, Al-Rdaydeh M, Habib S. Economic growth, foreign investment, tourism, and electricity production as determinants of environmental quality: empirical evidence from GCC region. Environ Sci Pollut Res. 2023;30(16):45768–80. https://doi.org/10.1007/s11356-023-25545-0.
33. GFN (2025) Global footprint network https://data.footprintnetwork.org/#/.
34. Granger CW, Yoon G (2002) Hidden cointegration. U of California, Economics Working Paper, (2002-02). https://doi.org/10.2139/ssrn.313831.
35. Grassberger P, Procaccia I. Characterization of strange attractors. Phys Rev Lett. 1983;50(5):346. https://doi.org/10.1103/PhysRevLett.50.346.
36. Grossman GM, Krueger AB (1991) Environmental impacts of a North American free trade agreement. Working paper 3914; NBER: Cambridge, MA, USA.
37. Huang H, Ali S, Solangi YA. Analysis of the impact of economic policy uncertainty on environmental sustainability in developed and developing economies. Sustainability. 2023;15(7):5860. https://doi.org/10.3390/su15075860.
38. Huang Y, Abidin SZU, Raza SMF. Investigation of resource curse hypothesis: the role of renewable energy and urbanization in realizing environmental sustainability in China. Environ Sci Pollut Res. 2023;30(37):86927–39. https://doi.org/10.1007/s11356-023-28300-7.

39. Hussain B, Naqvi SAA, Anwar S, Usman M. Effect of wind and solar energy production, and economic development on the environmental quality: is this the solution to climate change? Gondwana Res. 2023;119:27–44. https://doi.org/10.1016/j.gr.2023.01.012.
40. Ibrahim RL, Ajide KB, Usman M, Kousar R. Heterogeneous effects of renewable energy and structural change on environmental pollution in Africa: do natural resources and environmental technologies reduce pressure on the environment? Renew Energy. 2022;200:244–56. https://doi.org/10.1016/j.renene.2022.09.134.
41. Jahanger A, Usman M, Ahmad P. Investigating the effects of natural resources and institutional quality on CO2 emissions during globalization mode in developing countries. Int J Environ Sci Technol. 2022;20:1–20. https://doi.org/10.1007/s13762-022-04638-2.2.
42. Jahanger A, Usman M, Kousar R, Balsalobre-Lorente D. Implications for optimal abatement path through the deployment of natural resources, human development, and energy consumption in the era of digitalization. Resour Policy. 2023;86:104165. https://doi.org/10.1016/j.resourpol.2023.104165.
43. Jiang W, Kim H-S. Economic policy uncertainty and overinvestment: evidence from Korea. J Deriv Quant Stud. 2021;29(4):301–18. https://doi.org/10.1108/JDQS-05-2021-0010.
44. Jiang Y, Zhou Z, Liu C. Does economic policy uncertainty matter for carbon emission? Evidence from US sector level data. Environ Sci Pollut Res. 2019;26:24380–94. https://doi.org/10.1007/s11356-019-05627-8.
45. Khan I, Han L, Zhong R, Bibi R, Khan H. Income inequality, economic growth, renewable energy usage, and environmental degradation in the Belt and Road initiative countries: dynamic panel estimation. Environ Sci Pollut Res. 2023;30(19):57142–54. https://doi.org/10.1007/s11356-023-26273-1.
46. Lei X, Yang Y, Alharthi M, Rasul F, Raza SMF. Immense reliance on natural resources and environmental challenges in G-20 economies through the lens of COP-26 targets. Resour Policy. 2022;79:103101. https://doi.org/10.1016/j.resourpol.2022.103101.
47. Lin X, Zhao Y, Ahmad M, Ahmed Z, Rjoub H, Adebayo TS. Linking innovative human capital, economic growth, and CO2 emissions: an empirical study based on Chinese provincial panel data. Int J Environ Res Public Health. 2021;18(16):8503. https://doi.org/10.3390/ijerph18168503.
48. Liu M, Chen Z, Sowah JK Jr, Ahmed Z, Kirikkaleli D. The dynamic impact of energy productivity and economic growth on environmental sustainability in South European countries. Gondwana Res. 2023;115:116–27. https://doi.org/10.1016/j.gr.2022.11.012.
49. Luo W, Bai Z, Zheng S, Hui Y. A modified BDS test. Stat Probab Lett. 2020;164:108794. https://doi.org/10.1016/j.spl.2020.108794.
50. Ma W, Nasriddinov F, Haseeb M, Ray S, Kamal M, Khalid N, et al. Revisiting the impact of energy consumption, foreign direct investment, and geopolitical risk on CO2 emissions: comparing developed and developing countries. Front Environ Sci. 2022;10:1615. https://doi.org/10.3389/fenvs.2022.985384.
51. Mehmood U. Biomass energy consumption and its impacts on ecological footprints: analyzing the role of globalization and natural resources in the framework of EKC in SAARC countries. Environ Sci Pollut Res. 2022;29(12):17513–9. https://doi.org/10.1007/s11356-021-16586-4.
52. Mol APJ, Spaargaren G. Ecological modernisation theory in debate: a review. Environ Polit. 2000;9(1):17–49. https://doi.org/10.1080/09644010008414511.
53. Mujtaba A, Jena PK, Bekun FV, Sahu PK. Symmetric and asymmetric impact of economic growth, capital formation, renewable and non-renewable energy consumption on environment in OECD countries. Renew Sustain Energy Rev. 2022;160:112300. https://doi.org/10.1016/j.rser.2022.112300.
54. Murshed M, Haseeb M, Alam MS. The environmental Kuznets curve hypothesis for carbon and ecological footprints in South Asia: the role of renewable energy. GeoJournal. 2022;87(3):2345–72. https://doi.org/10.1007/s10708-020-10370-6.
55. Naseem S, Hu X, Mohsin M. Elongating the role of renewable energy and sustainable foreign direct investment on environmental degradation. Heliyon. 2023. https://doi.org/10.1016/j.heliyon.2023.e18421.
56. Ozturk I, Farooq S, Majeed MT, Skare M. An empirical investigation of financial development and ecological footprint in South Asia: bridging the EKC and pollution haven hypotheses. Geosci Front. 2023;15:101588. https://doi.org/10.1016/j.gsf.2023.101588.
57. Pan C, Cristia JFE, Irfan M, Pan Z, Ghardallou W, Tahir M, et al. Modelling the ecological footprints, climate change and economic growth nexus. Geol J. 2023;58(9):3348–67. https://doi.org/10.1002/gj.4767.
58. Pesaran MH, Shin Y, Smith RJ. Bounds testing approaches to the analysis of level relationships. J Appl Econom. 2001;16(3):289–326. https://doi.org/10.1002/jae.616.
59. Phillips PC, Perron P. Testing for a unit root in time series regression. Biometrika. 1988;75(2):335–46. https://doi.org/10.1093/biomet/75.2.335.
60. Ridwan M, Aspy NN, Bala S, Hossain ME, Akther A, Eleais M, et al. Determinants of environmental sustainability in the United States: analyzing the role of financial development and stock market capitalization using LCC framework. Discover Sustain. 2024;5(1):319.
61. Saidi K, Rahman MM. The link between environmental quality, economic growth, and energy use: new evidence from five OPEC countries. Environ Syst Decis. 2021;41:3–20. https://doi.org/10.1007/s10669-020-09762-3.
62. Saqib N, Ozturk I, Usman M, Sharif A, Razzaq A. Pollution haven or halo? How European countries leverage FDI, energy, and human capital to alleviate their ecological footprint. Gondwana Res. 2023;116:136–48. https://doi.org/10.1016/j.gr.2022.12.018.
63. Schnaiberg A (1980) The environment: From surplus to scarcity. Oxford University Press.
64. Seker F, Ertugrul HM, Cetin M. The impact of foreign direct investment on environmental quality: a bounds testing and causality analysis for Turkey. Renew Sustain Energy Rev. 2015;52:347–56. https://doi.org/10.1016/j.rser.2015.07.118.
65. Selmey MG, Elamer AA. Economic policy uncertainty, renewable energy and environmental degradation: evidence from Egypt. Environ Sci Pollut Res Int. 2023;30(20):58603–17. https://doi.org/10.1007/s11356-023-26426-2.
66. Sharif A, Kocak S, Khan HHA, Uzuner G, Tiwari S. Demystifying the links between green technology innovation, economic growth, and environmental tax in ASEAN-6 countries: the dynamic role of green energy and green investment. Gondwana Res. 2023;115:98–106. https://doi.org/10.1016/j.gr.2022.11.010.
67. Shin Y, Yu B, Greenwood-Nimmo M. Modelling asymmetric cointegration and dynamic multipliers in a nonlinear ARDL framework. Festschrift Honor Peter Schmidt Econom Methods Appl. 2014. https://doi.org/10.1007/978-1-4899-8008-3_9.

68. Syed QR, Bhowmik R, Adedoyin FF, Alola AA, Khalid N. Do economic policy uncertainty and geopolitical risk surge CO2 emissions? New insights from panel quantile regression approach. Environ Sci Pollut Res Int. 2022;29(19):27845–61. https://doi.org/10.1007/s11356-021-17707-9.
69. Uddin I, Usman M, Saqib N, Makhdum MSA. The impact of geopolitical risk, governance, technological innovations, energy use, and foreign direct investment on CO2 emissions in the BRICS region. Environ Sci Pollut Res. 2023. https://doi.org/10.1007/s11356-023-27466-4.
70. Udemba EN. A sustainable study of economic growth and development amidst ecological footprint: new insight from Nigerian Perspective. Sci Total Environ. 2020;732:139270. https://doi.org/10.1016/j.scitotenv.2020.139270.
71. Ullah A, Tekbaş M, Doğan M. The impact of economic growth, natural resources, urbanization and biocapacity on the ecological footprint: the case of Turkey. Sustainability. 2023;15(17):12855. https://doi.org/10.3390/su151712855.
72. 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. https://doi.org/10.1016/j.jclepro.2018.03.191.
73. Ulucak R, Khan SUD. Determinants of the ecological footprint: role of renewable energy, natural resources, and urbanization. Sustain Cities Soc. 2020;54:101996. https://doi.org/10.1016/j.scs.2019.101996.
74. Usman M, Kousar R, Makhdum MSA, Yaseen MR, Nadeem AM. Do financial development, economic growth, energy consumption, and trade openness contribute to increase carbon emission in Pakistan? An insight based on ARDL bound testing approach. Environ Dev Sustain. 2022. https://doi.org/10.1007/s10668-021-02062-z.
75. Waheed R, Sarwar S, Alsaggaf MI. Relevance of energy, green and blue factors to achieve sustainable economic growth: empirical study of Saudi Arabia. Technol Forecast Soc Change. 2023;187:122184. https://doi.org/10.1016/j.techfore.2022.122184.
76. Wang HJ, Geng Y, Xia XQ, Wang QJ. Impact of economic policy uncertainty on carbon emissions: evidence from 137 multinational countries. Int J Environ Res Public Health. 2021;19(1):4. https://doi.org/10.3390/ijerph19010004.
77. Wang J, Usman M, Saqib N, Shahbaz M, Hossain MR. Asymmetric environmental performance under economic complexity, globalization and energy consumption: evidence from the World's largest economically complex economy. Energy. 2023. https://doi.org/10.1016/j.energy.2023.128050.
78. Wang J, Yang L, Yang J. How sustainable environment is influenced by the foreign direct investment, financial development, economic growth, globalization, innovation, and urbanization in China. Environ Sci Pollut Res Int. 2023;30(17):49889–904. https://doi.org/10.1007/s11356-023-25634-0.
79. WDI (2025) World Development Indicators https://databank.worldbank.org/source/world-development-indicators#.
80. Wen Y, Onwe JC, Haseeb M, Saini S, Matuka A, Sahoo D. Role of technological innovation, renewable and non-renewable energy, and economic growth on environmental quality. Evidence from African countries. Front Energy Res. 2022;10:958839. https://doi.org/10.3389/fenrg.2022.958839.
81. WUI (2025). World Uncertainty Index (WUI): Global https://worlduncertaintyindex.com/.
82. Xu P, Zhang J, Mehmood U. How do green investments, foreign direct investment, and renewable energy impact CO2 emissions? Measuring the role of education in E-7 nations. Sustainability. 2023;15(19):14052. https://doi.org/10.3390/su151914052.
83. Xu Q, Khan S, Zhang X, Usman M. Urbanization, rural energy-poverty, and carbon emission: unveiling the pollution halo effect in 48 BRI countries. Environ Sci Pollut Res. 2023. https://doi.org/10.1007/s11356-023-29861-3.
84. Yang B, Usman M. Do industrialization, economic growth and globalization processes influence the ecological footprint and healthcare expenditures? Fresh insights based on the STIRPAT model for countries with the highest healthcare expenditures. Sustain Prod Consum. 2021;28:893–910. https://doi.org/10.1016/j.spc.2021.07.020.
85. Yang W, Zhang Y, Hu Y. Heterogeneous impact of economic policy uncertainty on provincial environmental pollution emissions in China. Sustainability. 2022;14(9):4923. https://doi.org/10.3390/su14094923.
86. Zafar MW, Zaidi SAH, Khan NR, Mirza FM, Hou F, Kirmani SAA. The impact of natural resources, human capital, and foreign direct investment on the ecological footprint: the case of the United States. Resour Policy. 2019;63:101428. https://doi.org/10.1016/j.resourpol.2019.101428.
87. Zarsky L(1999) Havens, halos and spaghetti: Untangling the evidence about foreign direct investment and the environment. In Foreign direct investment and the environment (pp. 47–74). OECD Publishing.
88. Zhengxia T, Haseeb M, Usman M, Shuaib M, Kamal M, Khan MF. The role of monetary and fiscal policies in determining environmental pollution: revisiting the N-shaped EKC hypothesis for China. Environ Sci Pollut Res Int. 2023;30(38):89756–69. https://doi.org/10.1007/s11356-023-28672-w.
89. Zhou R, Abbasi KR, Salem S, Almulhim AI, Alvarado R. Do natural resources, economic growth, human capital, and urbanization affect the ecological footprint? A modified dynamic ARDL and KRLS approach. Resour Policy. 2022;78:102782. https://doi.org/10.1016/j.resourpol.2022.102782.
90. Zivot E, Andrews DWK. Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. J Bus Econ Stat. 2002;20(1):25–44. https://doi.org/10.1198/073500102753410372.

Publisher's Note