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ARTICLE

Asymmetric Impact of Economic Complexity Index and Natural Resources Rents on Ecological Footprint in KSA: Empirical Evidence from Non-Linear ARDL

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ABSTRACT

This paper examines the asymmetric effects of economic complexity and natural resources on the ecological footprint in Saudi Arabia over the period 1995–2021 using the nonlinear autoregressive distributed lag (NARDL) approach. The results reveal that increases in economic complexity significantly exacerbate environmental pressure in the long run, with a 1% rise in economic complexity increasing the ecological footprint by 0.12%, while a 1% decrease reduces it by 0.39%, highlighting strong asymmetry. In contrast, both positive and negative shocks to natural resource rents contribute to environmental improvement; specifically, a 1% increase in natural resources reduces the ecological footprint by 0.11%, while a decrease further contracts it by 0.29%. The asymmetric Granger causality analysis indicates a unidirectional causality running from the ecological footprint to positive shocks in natural resources, as well as from negative shocks in natural resources to the ecological footprint, while a bidirectional causal relationship exists between economic complexity and the ecological footprint. These findings underscore the importance of incorporating economic complexity into Saudi

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Arabia's sustainability strategy by fostering innovation-driven diversification and green industrial transformation. To mitigate the environmental risks associated with economic development, policymakers should promote sustainable resource management, advance the green economy, and invest in innovative, low-pollution sectors.

Keywords: Ecological Footprint; Economic Complexity; Natural Resources; NARDL; Saudi Arabia

1. Introduction

The acceleration of economic development has intensified environmental pressures across the world[1,2]. Rising industrial activity, population growth, and unsustainable patterns of consumption have placed a significant strain on natural ecosystems. To capture these impacts comprehensively, the ecological footprint (EFP) has become a widely used indicator for assessing human demand in the biosphere. Unlike narrower indicators such as carbon dioxide emissions, the ecological footprint (EFP) captures a broader spectrum of environmental pressures, encompassing carbon emissions, cropland use, forest resources, grazing land, fishing grounds, and built-up land. This multidimensionality has made EFP an increasingly popular proxy for environmental degradation in contemporary research[3].

Saudi Arabia offers a particularly relevant case for examining the drivers of the ecological footprint due to its dual status as a resource-dependent economy and a country committed to structural transformation under Vision 2030[4]. Historically, the Kingdom has relied heavily on natural resource rents, especially oil revenues, which have shaped both its economic growth trajectory and environmental footprint. At the same time, Saudi Arabia is pursuing policies aimed at economic diversification and increasing its level of economic complexity. Understanding how these two forces—resource dependence and structural transformation—interact to influence environmental sustainability is crucial for informing national strategies that balance economic development with ecological preservation[5].

Several studies have examined the determinants of the ecological footprint, with natural resource rents (NRR) and the economic complexity index (ECI) gaining increasing attention[6–8]. Studies on resource rents suggest that heavy reliance on natural resources may exacerbate environmental degradation by encouraging over-extraction, rent-seeking behaviors, and dependence on energy-intensive industries[9,10]. This phenomenon, often linked to the resource curse hypothesis, implies that resource abundance can undermine sustainable development when governance and institutional quality are weak[11–13].

On the other hand, the economic complexity index reflects the diversity and sophistication of a country's productive capabilities. Higher levels of economic complexity are often associated with knowledge-intensive industries, technological advancement, and innovation that may contribute to improved resource efficiency and lower environmental pressure[14,15]. However, the literature presents mixed evidence. Some studies argue that complexity fosters environmental sustainability by enabling the diffusion of green technologies[16–18], while others highlight the risk that sophisticated industrial structures can increase ecological footprints if production remains carbon- or resource-intensive[19].

Beyond these two determinants, recent methodological advances emphasize the importance of asymmetry in analyzing economic-environment linkages. The nonlinear autoregressive distributed lag (NARDL) model enables researchers to account for the possibility that positive and negative shocks in the explanatory variables exert asymmetric effects on environmental indicators. For instance, increases in natural resource rents may accelerate environmental degradation more strongly than equivalent decreases may reduce it. Similarly, improvements in economic complexity might reduce ecological pressure, but declines in complexity may not have the same magnitude of negative effect. Studies employing asymmetric methods have provided valuable insights, but the integration of economic complexity and natural resource rents within this framework remains limited.

Saudi Arabia faces a dual challenge. On the one hand, its dependence on natural resources has historically contributed to environmental pressures reflected in its rising ecological footprint[20]. On the other hand, the nation is pursuing economic diversification and greater complexity under Vision 2030, which emphasizes technological innovation, industrial diversification, and environmental sustainability[21]. Despite the progress in this field, several gaps persist. First, while ecological footprints have been widely used in sustainability research, few studies jointly assess the roles of economic complexity and natural resource rents as determinants of EFP. The interaction between structural transformation and resource dependence remains underexplored, particularly in the context of resource-rich economies. Second, much of the existing literature adopts symmetric approaches, implicitly assuming that increases and decreases in complexity or rents affect EFP in the same way. This overlooks the possibility of asymmetric impacts that may carry distinct policy implications. Third, empirical evidence for Saudi Arabia is scarce, with most studies focusing on global or multi-country samples. Given the Kingdom's unique economic structure, heavy reliance on resource rents, and ambitious diversification agenda, country-specific analysis is needed.

Accordingly, the primary objective of this study is to investigate the asymmetric effects of economic complexity and natural resource rents on Saudi Arabia's ecological footprint. The central research question of this study is: How do economic complexity and natural resource rents, through both positive and negative shocks, affect Saudi Arabia's ecological footprint? This question is important for several reasons. First, the ecological footprint is a comprehensive indicator that captures multiple dimensions of environmental pressure, making it particularly suitable for assessing sustainability challenges in rapidly developing economies. Second, Saudi Arabia represents a unique case due to its heavy reliance on natural resource rents alongside its ongoing structural transformation under Vision 2030. Understanding the environmental consequences of this transition is crucial for designing policies that reconcile economic diversification with ecological sustainability. Third, despite growing interest in economic complexity and resource dependence, existing studies rarely examine their joint effects on the ecological footprint, especially in resource-rich economies. Addressing this gap provides new insights into how structural change and resource dependence interact to shape environmental outcomes.

To address the research question, the study adopts an asymmetric empirical framework using the nonlinear autoregressive distributed lag (NARDL) model. This approach allows the analysis to distinguish between the effects of positive and negative shocks in economic complexity and natural resource rents on the ecological footprint. Unlike conventional symmetric models, the NARDL model captures nonlinear dynamics that may carry important policy implications, particularly in economies undergoing structural transformation. By applying this methodology to Saudi Arabia's time-series data, the study provides country-specific evidence on the environmental implications of resource reliance and economic diversification.

The rest of the paper is organized as follows: Section 2 reviews the existing literature. Section 3 for data and methodology, Section 4 will provide empirical results; and Section 5 is to draw main conclusions and policy implications.

2. Literature Review

The purpose of this section is to provide a brief review of the studies that have addressed the EF, ECI, and NRR relationship. The association between ECI and environmental quality has been analyzed in several research but yielded conflicting findings. In this point of view, Doğan et al.[22] explored the relationship between ECI and EFP. By applying the QARDL model and Granger quantile causality tests, they found a positive effect of ECI on the EFP to be significant. In addition, they argued about the causal connection between EC and the EFP. Pata[23] also examined the correlation between ECI and EFP in the US for annual data from 1980 to 2016. The results of the study also confirmed that there was a U-shaped ECI-to-EFP relationship, which indicates that when the threshold crosses, ECI contributes by diminishing EFP.

Neagu[24] has analyzed the relationship between ECI and EFP in 48 countries. He finds that there is a positive long-run relationship between EFP and ECI. Further, Yilanci and Pata[25] used the ARDL methodology to examine the impact of ECI on EFP in China over the period 1965 to 2016. They reveal that ECI has a positive impact on the EFP in both the short and long term. Kazemzadeh et al.[26] scrutinized the effect of ECI on the EFP of twenty-five countries spanning 1970–2016. Their analysis using panel quantile regression demonstrates that the ECI has a positive impact on the EFP at the 10% and 25% quantiles. However, this was not true for the higher quantiles. Rafique et al.[27] examined the association between ECI and EFP for ten economies from 1980 to 2017. They concluded that the ECI has a long-term positive and significant impact on the EFP.

However, some studies showed that the EFP and ECI have a negative association, contradicting those which indicated a positive relationship between them. Boleti et al.[28] investigate the relationship between ECI and environmental performance in 88 countries from 2002 to 2012. Applying various econometric methodologies (fixed effects and random effect models, 2SLS/IV fixed effects), they found that transitioning to higher ECI levels results in enhanced environmental performance. Likewise, Neagu and Teodoru[29] investigated the relationship between ECI and environmental quality in EU member states. The findings revealed an inverse association between ECI and EFP. Chu[30] demonstrated that ECI is related to higher degradation at early growth. However, ECI prevails as an effective policy in reducing environmental quality degradation, beyond a certain threshold. Therefore, we propose the following hypothesis:

H1. *Economic complexity significantly affects the level of ecological footprint in KSA.*

Beyond environmental studies, recent contributions emphasize the role of structural transformation, financial conditions, and dynamic spillovers in shaping economic complexity and long-term outcomes. For example, Kyriazis et al.[31] show that financial stress in banking intermediaries can crowd out high-tech and complex productive activities, suggesting that institutional and financial factors may critically influence the evolution of economic complexity and its sustainability implications. Likewise, Dimitriadis et al.[32] emphasize the importance of dynamic international spillovers and nonlinear transmission mechanisms, reinforcing the relevance of adopting asymmetric and dynamic econometric approaches when analyzing complex economic relationships.

Regarding the relationship between NRR and EFP, the literature also reports inconclusive evidence. In fact, Chekouri et al.[33] tried to explore the impact of NRR on Algeria's EFP during the period from 1970 to 2018. The authors used two different methods, namely, the ARDL and QQR models. They recommended that the NRR be increased by the EFP. Also, they showed that NRR have a positive and significant impact on the EFP at middle and upper quantiles. But with quantiles below, this impact becomes less strong. Ahmad et al.[34] investigated the nexus between EFP and natural resources across 22 developing nations. The result implies that environmental deterioration is mitigated by technological change and NRR enhance the EFP. Awosusi et al.[35] investigated the relationship between EFP and NRR for the BRICS nations from 1992 to 2018. They observed that NRR are important in the EFP. The effect of the NRR rate on EFP in Pakistan was also explored by Hassan et al.[7]. NRR was also found to have a positive influence on EFP, and that EFP is the cause of NRR in both directions. This finding is consistent with that of Langnel et al.[36], who reported a trend for increased EFP with more NRR. A negative effect between the two was also confirmed by other studies. In this context, Zafar et al.[37] reported a negative association between NRR and environmental quality in the US.

Although understanding the relationship between ECI, NRR, and EFP is essential, this area has received limited academic attention. To address this gap, the present study develops a theoretical framework linking these three factors (see **Figure 1**). A review of the literature reveals that while most existing studies focus primarily on CO_2 emissions, only a few have examined the role of ECI and NRR as determinants of ecological degradation. As a result, the influence of ECI and NRR on environmental deterioration remains uncertain, with no clear consensus in the literature. This study aims to resolve this ambiguity by proposing the following hypothesis for Saudi Arabia, grounded in prior empirical findings:

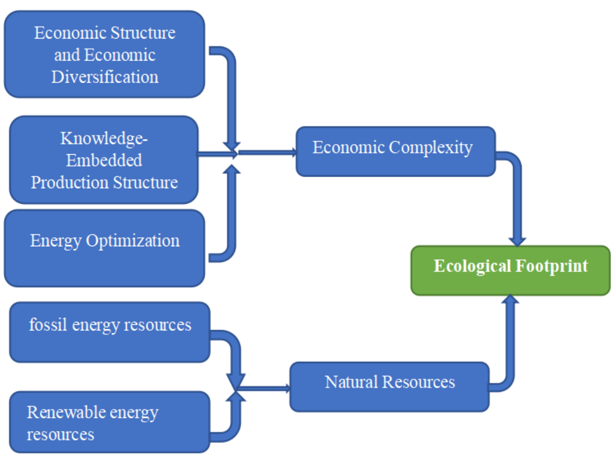


Figure 1. Pictorial view of the analysis framework.

H2. *Natural resources rents significantly affect the level of ecological footprint in KSA.*

Literature Gaps

Despite the growing body of literature examining the relationship between economic complexity, natural resources, and environmental degradation, several important gaps remain. First, most existing studies rely predominantly on CO_2 emissions as a proxy for environmental quality, while the use of the ecological footprint, which captures broader environmental pressures, remains relatively limited. Second, most of the empirical evidence is based on cross-country or panel data analyses, which may obscure country-specific dynamics, particularly in resource-dependent economies such as Saudi Arabia. Third, prior studies largely adopt linear modeling approaches, overlooking potential nonlinear and asymmetric effects of economic complexity and natural resources on environmental outcomes. Fourth, although endogeneity and feedback effects are often acknowledged, relatively few studies explicitly examine dynamic and asymmetric causality relationships, especially in a single-country time-series context. Finally, the combined role of economic complexity and natural resource rents in shaping the ecological footprint remains insufficiently explored, leaving limited guidance for sustainability-oriented structural transformation policies in oil-rich economies.

3. Data and Methodology

3.1. Data

In this study, environmental degradation is assessed using the ecological footprint (EFP), the Economic Complexity Index (ECI), and natural resource rents (NRR). The EFP is expressed in global hectares per capita, while the ECI reflects export diversification and product ubiquity. NRR is measured as a percentage of GDP. The analysis covers the period from 1995 to 2021, based on data availability. **Table 1** provides detailed descriptions of all variables employed in the study, including their measurement units and data sources. This presentation enhances transparency and enables readers to clearly understand the foundations of empirical investigation.

Table 1. Measurement and definition of the study variables.

Variables	Symbol	Definition	Sources
Ecological Footprint	EFP	Per capita Ecological footprint measured by global hectares	GFN
Economic complexity index	ECI	Economic complexity measured by export diversification and ubiquity	Observatory of Economic Complexity
Natural resources rents	NRR	Natural Resource rents (% of GDP)	WDI

The presentation of the descriptive statistics analysis is given in **Table 2** below. This table incorporates the mean values, as well as the minimum and maximum values, for each variable that was selected for investigation. The standard deviation is the deviation of the values from their mean during the period, where the mean value is the average value for the variable. All variables have positive average values. The current investigation employed the Jarque-Bera test to validate the normality of the selected variables. The Jarque-Bera test affirms the rejection of the null hypothesis at a significance level of 1%, indicating that every factor exhibits non-linear behavior.

Table 2. Descriptive statistics analysis.

Variable	EFP	ECI	NRR
Mean	4.841	0.023	35.826
Median	5.031	0.025	34.596
Maximum	6.853	0.820	55.024
Minimum	2.358	−0.870	17.318
Std. Dev.	1.218	0.437	10.701
Skewness	−0.375	−0.140	0.115
Kurtosis	2.246	2.486	1.829
Jarque-Bera	1.274	0.385	1.602
Probability	0.528	0.824	0.448
EFP	1		
ECI	0.045	1	
NRR	−0.001***	−0.659***	1

Notes: *** and ** denote statistical significance at the 1% and 5% levels, respectively.

In **Table 2**, the results of the correlation analysis indicate that ECI was positively correlated with EFP. Additionally, NRR has a negative correlation with EFP. Additionally, an overview of the dataset, along with the methodological framework and the sequence of analytical steps employed in the study, is presented in **Figure 2**, providing a clear visualization of how the data and methods are integrated in the research.

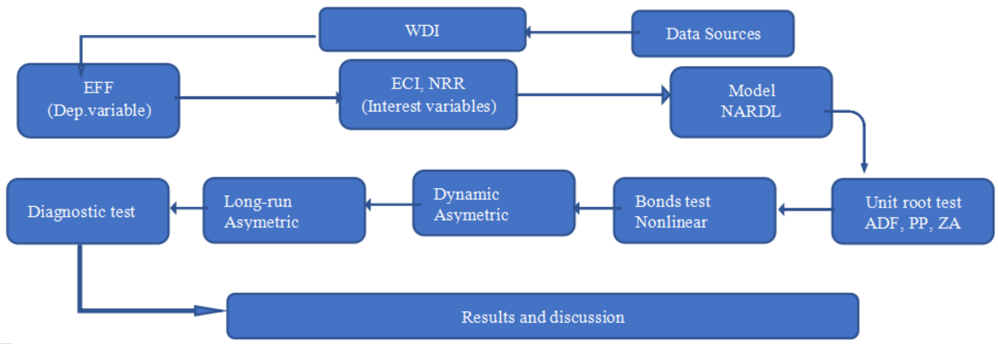


Figure 2. Methodology flow diagram.

3.2. Methodology

In the context of this article, the objective is to verify whether the relationship between EFP, ECI, and NRR is symmetrical or asymmetrical. The current study constructs a research framework, as illustrated in **Figure 2**, building on the work of previous studies[27,38,39].

In the context of this article, the objective is to verify whether the relationship between EFP, ECI, and NRR is symmetrical or asymmetrical. To achieve this, the study employs the NARDL model, processed using STATA v.17.0 software. This approach is chosen for its ability to capture the asymmetric impacts of positive and negative shocks, offering a more nuanced analysis compared to the linear ARDL model. By doing so, the research extends the traditional linear ARDL model framework, providing deeper insights into the differing impacts of economic variables on the EFP.

In this context, adopting the ARDL technique, which already includes the entire process as proposed by Pesaran et al.[40], we obtain the following specification:

$$\Delta lnEFP_t = \alpha_0 + \sum\nolimits_{i=0}^{p} \alpha_1 \Delta lnEFP_{t-i} + \sum\nolimits_{i=0}^{p} \alpha_2 \Delta lnECI_{t-i} + \alpha_3 lnECI_{t-1} + \varepsilon_t, \tag{1}$$

$$\Delta lnEFP_t = \beta_0 + \sum\nolimits_{i=0}^{p} \beta_1 \Delta lnEFP_{t-i} + \sum\nolimits_{i=0}^{p} \beta_2 \Delta lnNRR_{t-i} + \beta_3 lnNRR_{t-1} + \omega_t. \tag{2}$$

In Equations (1) and (2), the coefficients α_1, α_2, β_1, β_2 attached to the variables represent the short-term effects, with Δ the first difference operator, while α_3 and β_3 are the long-term coefficients, and ϵ_t and ω_t are the error terms.

Subsequently, in this paper, to be able to analyze the symmetric or asymmetric link between explanatory variables and climate change approached by the ecological footprint, we adopt the NARDL model that was used by many researchers in environmental economics, such as Munir and Riaz[41] and Rahman and Ahmad[42]. The NARDL model exhibits benefits in comparison to the VECM and other alternative techniques, owing to its characteristic of order integration restriction[43]. The other techniques of cointegration solely accommodate variables with an integration order of one, whereas the NARDL model can be employed regardless of the nature of variables thanks to its flexibility[44]. Equations (1) and (2), when subjected to consideration of both positive and negative changes in the explanatory variables, can be expressed as follows:

$$\Delta lnEFP_t = \beta_0 + \sum\nolimits_{j=1}^{n-1} \beta_1 \Delta lnEFP_{t-j} + \sum\nolimits_{j=0}^{n2} \left(\beta_2^{+} \Delta lnECI_{t-j}^{+} + \beta_3^{-} \Delta lnECI_{t-j}^{-}\right) + \alpha_1 lnEFP_{t-1} + \alpha_2^{+} lnECI_{t-1}^{+} + \alpha_3^{-} lnECI_{t-1}^{-} + \varepsilon_t \tag{3}$$

$$\Delta lnEFP_t = \lambda_0 + \sum\nolimits_{j=1}^{n-1} \lambda_1 \Delta \ln EFP_{t-j} + \sum\nolimits_{j=0}^{n2} \left(\lambda_2^{+} \Delta lnNRR_{t-j}^{+} + \lambda_3^{-} \Delta lnNRR_{t-j}^{-}\right) + \theta_1 lnEFP_{t-1} + \theta_2^{+} lnNRR_{t-1}^{+} + \theta_3^{-} lnNRR_{t-1}^{-} + \upsilon_t. \tag{4}$$

To estimate the short-term NARDL elasticities, the following equation can be used:

$$\begin{aligned}\Delta lnEFP_t = \beta_0 + \sum\nolimits_{j=1}^{n-1} \beta_1 \Delta lnEFP_{t-j} \\ + \sum\nolimits_{j=0}^{n2} \left(\beta_2^+ \Delta lnECI_{t-j}^+ + \beta_3^- \Delta lnECI_{t-j}^-\right) \\ + \eta_1 ECT_{t-1} + \varepsilon_t,\end{aligned} \tag{5}$$

$$\begin{aligned}\Delta lnEFP_t = \lambda_0 + \sum\nolimits_{j=1}^{n-1} \lambda_1 \Delta lnEFP_{t-j} \\ + \sum\nolimits_{j=0}^{n2} \left(\lambda_2^+ \Delta lnNRR_{t-j}^+ + \lambda_3^- \Delta lnNRR_{t-j}^-\right) \\ + \eta_2 ECT_{t-1} + \upsilon_t.\end{aligned} \tag{6}$$

According to Equation (4), ECI, and NRR have both positive and negative effects:

$$\begin{aligned} lnECI_t = lnECI_t^+ + lnECI_t^-, \\ lnNRR_t = lnNRR_t^+ + lnNRR_t^-. \end{aligned} \tag{7}$$

Where $lnECI_t^+ + lnECI_t^-$, and $lnNRR_t^+ + lnNRR_t^-$ represent the partial sum processes that gather together both positive and negative changes, respectively.

$$\begin{aligned} lnECI_t^+ = \sum\nolimits_{j=1}^{t} max(\Delta lnECI_j, 0), \\ lnECI_t^- = \sum\nolimits_{j=1}^{t} min(\Delta lnECI_j, 0), \end{aligned} \tag{8}$$

$$\begin{aligned} lnNRR_t^+ = \sum\nolimits_{j=1}^{t} max(\Delta lnNRR_j, 0), \\ lnNRR_t^- = \sum\nolimits_{j=1}^{t} min(\Delta lnNRR_j, 0). \end{aligned} \tag{9}$$

The Standard Wald tests are used to test long-term symmetry ($\alpha^+ = \alpha^-$) and ($\theta^+ = \theta^-$), and asymmetry ($\alpha^+ \neq \alpha^-$) and ($\theta^+ \neq \theta^-$). Based on a unit change in $lnECI_t^+$, $lnECI_t^-$, $lnNRR_t^+$, and $lnNRR_t^-$, the effects of asymmetric cumulative dynamic multipliers on $lnEFP_t$ are obtained as follows:

$$\begin{aligned} s_{h,ECI}^+(ECI) = \sum\nolimits_{j=0}^{h} \frac{\partial lnEFP_{t+j}}{\partial lnECI_{t-1}^+}, \\ s_{h,ECI}^-(ECI) = \sum\nolimits_{j=0}^{h} \frac{\partial lnEFP_{t+j}}{\partial lnECI_{t-1}^-}, \end{aligned} \tag{10}$$

$$\begin{aligned} s_{h,NRR}^+(NRR) = \sum\nolimits_{j=0}^{h} \frac{\partial lnEFP_{t+j}}{\partial lnNRR_{t-1}^+}; \\ s_{h,NRR}^-(NRR) = \sum\nolimits_{j=0}^{h} \frac{\partial lnEFP_{t+j}}{\partial lnNRR_{t-1}^-}. \end{aligned} \tag{11}$$

As previously mentioned, the dissimilar reactions of the variable being studied to both positive and negative changes in the variables being examined are depicted using dynamic multipliers. By analyzing these multipliers, we observe the dynamic adjustment from the initial state of balance to the new state of balance within the system variable after the variations that affect the system.

4. Empirical Results

4.1. Stationary Test

Stationarity is a very important concept in time series analysis. When working with non-stationary series, conventional tests are biased, and the regressions performed are spurious. A series is said to be stationary when it maintains a constant distribution over time. To study whether the series is stationary, to determine its order of integration, we will use the ADF and PP tests. Thus, we will only be able to validate the stationarity of a series if the hypothesis of the presence of a unit root is rejected by both tests. In addition, we also use the ZA test to account for the potential bias relating to structural change in the evolution of the Saudi economy.

In **Table 3**, the stationarity results above show that the series selected—EFP, ECI, and NRR—are all differenced-stationary (DS) processes and are integrated of order 1 at the 1% level. The results of the PP and ADF tests corroborate with the ZA for all the variables.

4.2. Cointegration Test

The results show that the variables EFP, ECI, and NRR are stationary at I(1). In this case, the ARDL bound testing approach can be used in this situation. The NARDL approach separates the explanatory variable into positive and negative variations, enabling a more detailed analysis of its effects. Therefore, based on our analysis using the NARDL models (1) and (2), we conclude that if the static values of the F- and *t*-tests exceed the upper bounds for both models, a long-term cointegration relationship is present. As shown in **Table 4**, we reject the null hypothesis, since the estimated F-test value is significantly higher than the critical value at a 5% significance level. This conclusion is further supported by the *t*-test results, where the computed value also exceeds the critical value.

Table 3. Results of the unit root test.

	ADF	PP	ZA	Breaks	ADF	PP	ZA	Breaks
		Level				1st difference		
EFP	−1.274	−1.274	−3.393	1999	−5.509***	−5.509***	−7.988***	2000
ECI	−1.925	−1.953	−3.527	2016	−5.292***	−6.011***	−6.048***	2008
NRR	−1.878	−1.836	−3.136	2014	−4.988***	−5.131***	−6.034***	2009

Note: *** denotes the level of significance at 1%.

Table 4. Cointegration results from the Bound test.

Model 1 EFP/ECI	Model 2 EFP/NRR		Model 1 EFP/ECI	Model 2 EFP/NRR	
F = 15.361***	F = 10.145***		t = −7.021***	t = −5.368***	
Lower Bound	Upper Bound	Significance	Lower Bound	Upper Bound	Significance
5.25	6.18	0.01	−3.56	−4.23	0.01
4.10	4.48	0.05	−2.68	−3.85	0.05
3.80	4.25	0.1	−2.13	−3.66	0.1

Note: *** denotes the level of significance at 1%. Based on Pesaran et al. (2001), the critical values were determined.

4.3. NARDL Long-Run and Short-Run Estimation

The long-run asymmetric NARDL estimations provide strong evidence that economic complexity (ECI) and natural resource rents (NRR) exert significant and nonlinear effects on the ecological footprint (EFP) in Saudi Arabia. In **Table 5** (Model 1), the estimated long-run coefficients reveal a pronounced asymmetric impact of economic complexity on environmental degradation. A positive change in economic complexity (ECI^+) shows a coefficient of 0.123, significant at the 10% level, implying that increases in economic sophistication tend to raise the ecological footprint in the long run. For Saudi Arabia, this suggests that ongoing industrialization, export diversification, and advancement toward more complex production structures may initially exacerbate environmental pressure through higher energy consumption, industrial emissions, and resource use. However, a negative change in economic complexity (ECI^-) yields a much larger coefficient of −0.391, significant at the 1% level, indicating that reductions in complexity substantially decrease environmental pressure. This strong asymmetry highlights that scaling back complex economic activities leads to a sharper environmental improvement than the deterioration caused by expanding them. The error correction coefficient ECT_{t-1} = −0.264 implies that approximately 26.4% of short-run environmental disequilibrium is corrected each year, reflecting moderate adjustment dynamics within the Saudi economy. According to this empirical study, the results were consistent with those obtained by Kibria [39].

In **Table 5** (Model 2), natural resource rents also display asymmetric long-run effects on the ecological footprint. A positive shock to NRR (NRR^+) has a statistically significant negative coefficient of −0.110, suggesting that increases in oil and gas revenues in Saudi Arabia contribute to reducing environmental pressure. Economically, this may reflect the strategic use of resource revenues to finance environmental protection, technological upgrades, renewable energy investments, and efficiency-enhancing infrastructure aligned with national sustainability goals. Conversely, a negative shock to NRR (NRR^-) shows a stronger negative coefficient of −0.293, significant at the 5% level, indicating that declines in resource rents lead to a more pronounced reduction in the ecological footprint. This finding underscores the environmental benefits of lowering resource dependency and extraction intensity. The adjustment speed in this model is relatively faster, as shown by ECT_{t-1} = −0.352, meaning that about 35.2% of short-run deviations from equilibrium are corrected annually.

On the other hand, the short-run estimated are reported in **Table 6**. The results indicate that EFP responds significantly negatively to a positive shock in the ECI. This result diverges somewhat from the long-term evaluation presented in Model (1). Conversely, a negative shock in ECI leads to a significant increase in the EFP in the short term. This result indicates that short-term improvements in industrial sophistication and technological progress can temporarily reduce environmental pressures, possibly due to efficiency gains and cleaner production techniques. However, over the long term, the expansion of complex industries may increase resource use and emissions unless accompanied by strong environmental regulations and green innovation incentives. Thus, policies promoting economic diversification should prioritize sectors that combine high value-added with low ecological impact, such as renewable energy, sustainable manufacturing, and digital services, ensuring that industrial advancement contributes to both economic growth and environmental protection. Our findings align with those of Kibria[39], who also found that ECI negatively impacts the EFP. However, other studies, such as Neagu[24], suggest that ECI has a positive effect on the EFP.

Table 5. Long-term asymmetry of the NARDL model.

Models	Variables	Coefficient	Std-Error	Prob.
Model 1	ECI^{+}	0.123^{*}	1.720	0.059
EFP/ECI	ECI^{-}	-0.391^{***}	2.821	0.010
	ECM(−1)	-0.264^{***}	0.747	0.000
	Constant	3.250^{**}	0.207	0.045
Model 2	NRR^{+}	-0.110^{**}	0.041	0.018
EFP/NRR	NRR^{-}	-0.293^{**}	0.044	0.021
	ECM(−1)	-0.352^{***}	0.897	0.000
	Constant	4.427^{**}	0.130	0.048

Note: Significant levels of 1%, 5%, and 10%, respectively, are denoted by ***, **, and *.

Table 6. Short-term asymmetry of the NARDL model.

Models	Variables	Coefficient	Std-Error	Prob.
Model 1	ΔECI_t^{+}	-0.181^{***}	3.094	0.000
EFP/ECI	ΔECI_{t-1}^{+}	-0.110^{**}	2.130	0.020
	ΔECI_{t-2}^{+}	-0.201^{**}	2.136	0.033
	ΔECI_t^{-}	0.367^{***}	4.085	0.000
	ΔECI_{t-1}^{-}	0.124^{***}	4.120	0.000
	ΔECI_{t-2}^{-}	0.367^{*}	1.087	0.067
Model 2	ΔNRR_t^{+}	0.110^{*}	1.049	0.082
EFP NRR	ΔNRR_t^{-}	-0.163^{**}	2.065	0.019
	ΔNRR_{t-1}^{-}	-0.203^{**}	1.987	0.071
	ΔNRR_{t-2}^{-}	-0.305^{*}	1.180	0.079

Note: Significant levels of 1%, 5%, and 10%, respectively, are denoted by ***, **, and *.

In contrast, the results show that a continuous increase in the availability of NRR has a significant positive impact on the EFP. However, a reduction in NRR leads to a pronounced negative effect on the EFP in the short term. This finding aligns with the study by Gupta et al.[45], which indicates a negative effect of NRR on EFP. Conversely, Ahmed et al.[46] reported a positive relationship between the two variables, while Alvarado et al.[6] proposed a neutrality hypothesis between NRR and EFP. The robustness of Equations (5) and (6) is evident, as the error correction term (ECT_{t-1}) is both significant and negative at the 1% level.

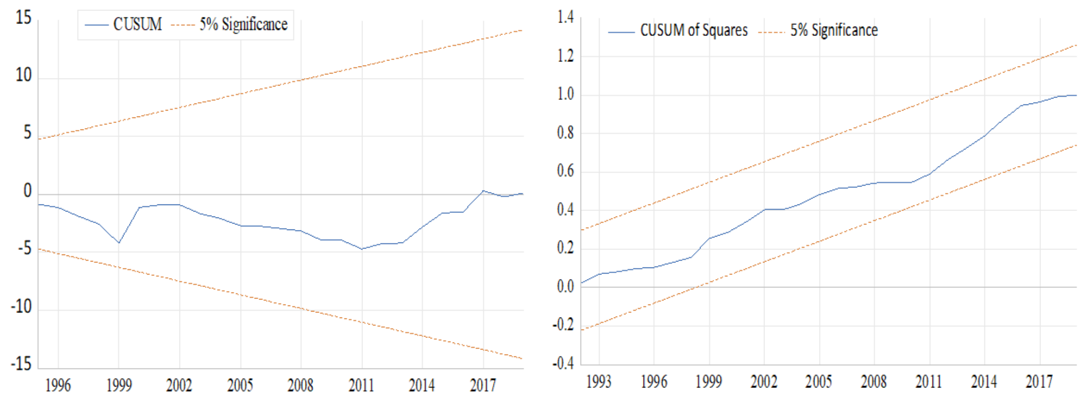
Table 7 reports the results for heteroscedasticity, normality, and serial correlation for Equations (3) and (4). The findings confirm that the models have no serial correlation or heteroscedasticity problems. It appears that the variables are normally distributed based on the Jarque-Bera test. Furthermore, the Wald test results confirm that positive and negative shifts in both ECI and NRR produce significant asymmetric effects on the EFP in both the short and long term.

Table 7. Diagnostic analysis.

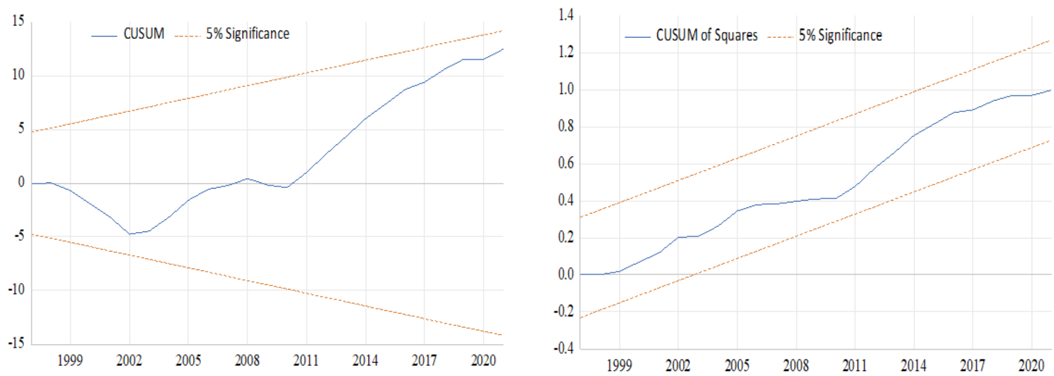
Diagnostic Tests	Model (1) EFP/ECI		Model (2) EFP/NRR	
	F-Statistic	**Prob.**	**F-Statistic**	**Prob.**
W_{LR}	213.354***	0.000	354.241***	0.009
W_{SR}	251.684***	0.007	412.521***	0.002
Breusch-Pagan test for heteroskedasticity	2.681	0.798	3.658	0.647
Breusch-Godfrey LM test for autocorrelation	1.588	0.928	1.956	0.871
Jarque–Bera test	5.981	0.128	4.231	0.201
Ramsey RESET test	3.547	0.254	3.689	0.322
ARCH test	1.681	0.448	2.011	0.512

Note: *** denotes the level of significance at 1%.

After checking the structural stability of the models, stability techniques were also used in the study. The cumulative sums (CUSUM) of recursive and cumulative squares plots of the NARDL regressions show that the models are stable since they are all within the 95% confidence interval in **Figure 3**.



(a) Model 1: EFP/ECI.



(b) Model 2: EFP/NNR.

Figure 3. Plot of the CUSUM and CUSUM of squares statistics.

Figure 4 illustrates the dynamic asymmetric effects of positive and negative shocks in ECI on the EFP in Saudi Arabia. The graph shows that an increase in ECI has a positive and statistically significant long-run impact on EFP, indicating that industrial diversification and technological sophistication currently remain energy and resource intensive. In contrast, a decrease in ECI leads to a stronger reduction in EFP, suggesting an asymmetric response where environmental improvements are more sensitive to economic slowdowns or declines in industrial complexity.

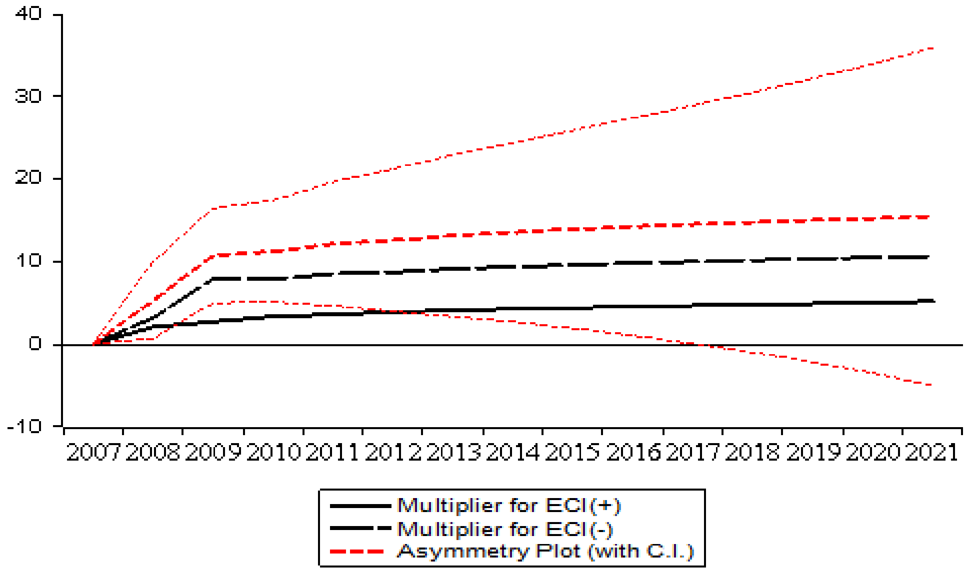


Figure 4. NARDL Dynamic Multiplier Graph for ECI.

Figure 5 presents the asymmetric effects of positive and negative shocks in natural resource rents (NRR) on the ecological footprint. Both positive and negative changes in NRR are associated with reductions in EFP, although the effect of negative shocks (declines in resource rents) appears slightly stronger. This finding suggests that Saudi Arabia has made progress in managing its natural resource revenues through cleaner extraction processes, diversification policies, and renewable energy investment funded by oil income. The asymmetry also indicates that periods of declining NRR encourage policy reforms and efficiency improvements, leading to lower ecological pressures.

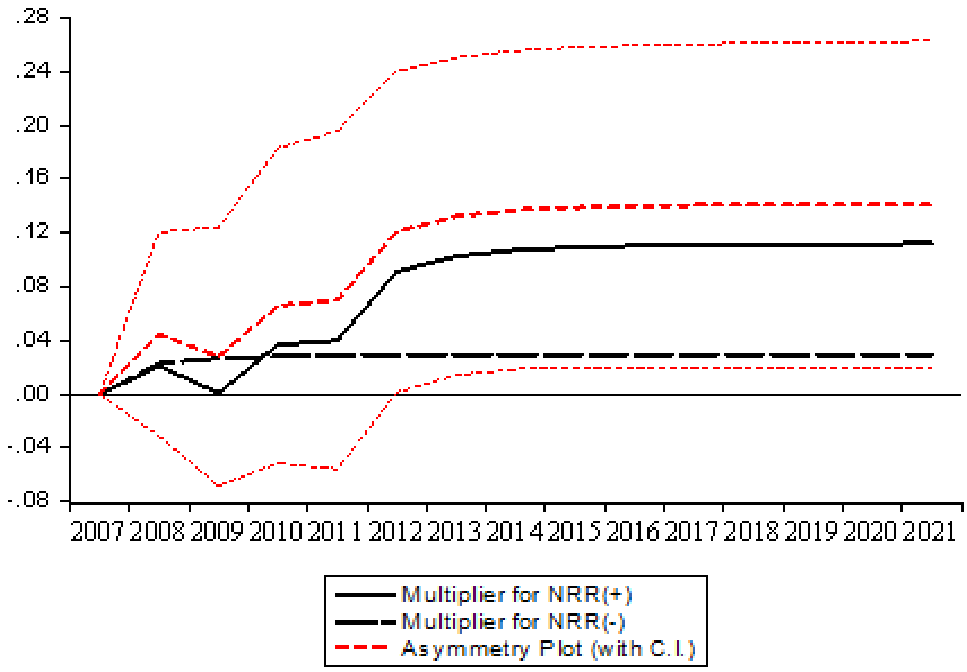


Figure 5. NARDL Dynamic Multiplier Graph for NRR.

4.4. Causality Test

The causal relationship between the decomposed ECI and NRR, considering both positive and negative shocks, was explored using symmetric and asymmetric causality tests. Additionally, non-asymmetric causality between the EFP and ECI variables was analyzed. In **Table 8**, the results showed a one-way relationship, indicating a directional impact from ecological footprints to negative shocks in natural resources (NRR^{-}). Consequently, Saudi Arabia's natural resources will be hampered by carbon emissions. For instance, because of increasing emissions, environmentalists find themselves compelled to implement a sustainable environmental policy mechanism, such as imposing a carbon tax, to regulate and control emissions [47].

In this way, due to sustainable environmental policies, renewable energy resources will be given more importance, which will lower natural resource demand even though it is less price elastic. Therefore, the shock of natural resource prices is adversely affected by this outlay. There are unidirectional relationships found from positive shocks of natural resources (NRR^{+}) to ecological footprints. These findings reveal that natural resources positively affect the ecological footprints as per the environmental situations.

Table 8. Causality asymmetry and non-asymmetry.

Variables	ΔEFP	ΔECI_t^{+}	ΔECI_t^{-}	ΔNRR_t^{+}	ΔNRR_t^{-}
			Model (1): EFP/ECI		
ΔEFP	-	15.247***	11.519***	-	-
ΔECI_t^{+}	8.225***	_	5.698*	_	_
ΔECI_t^{-}	10.698***	7.365*	-	-	-
			Model (2): EFP/NRR		
ΔEFP	-	-	-	6.984**	4.684
ΔNRR_t^{+}	2.365	_	_	_	1.320
ΔNRR_t^{-}	3.687**	-	-	13.654***	_

Note: ***, **, and * denote the level of significance at 1%, 5%, and 10%, respectively.

Additionally, the results also reveal a bi-directional relationship between positive and negative shocks of EC (EC^{+}, EC) and EFP. These results have notable political implications. Policymakers may need to address both aspects simultaneously, recognizing the interdependence between economic activities and their environmental consequences. The interpretation of the causality tests could be strengthened by framing the results within a policy feedback loop perspective. The tests suggest that ECI causes changes in EFP. This may imply that industrial upgrading shapes environmental outcomes, which in turn may trigger regulatory responses, technological shifts, or shifts in resource allocation that feed back into ECI. Similarly, NRR drives EFP; policy responses to environmental degradation (e.g., subsidy reforms, diversification efforts) could influence future dependence on natural resource rents.

The apparently paradoxical findings can be understood within the broader context of Saudi Arabia's dual economic structure and transition phase. For instance, the positive effect of ECI on the EFP in the short term reflects the dominance of energy-intensive and resource-dependent industries, such as petrochemicals and heavy manufacturing, that contribute to higher emissions despite being technologically advanced. However, as industrial upgrading progresses and cleaner production technologies are adopted, the environmental impact of complexity may diminish, leading to improved sustainability outcomes in the long run.

Similarly, the relationship between NRR and environmental pressure may appear contradictory because resource wealth can both finance green investment and reinforce fossil-fuel dependency. In the Saudi context, high oil revenues have historically encouraged intensive energy use, but they also provide fiscal space for diversification and renewable energy initiatives under Vision 2030. This dual role helps explain why NRR may exhibit mixed effects depending on policy orientation.

5. Conclusion and Policy Implications

5.1. Summary of the Findings

This study makes a significant contribution to the existing literature on the relationship between ECI, NRR, and their impact on the EFP. Our study focused on a country rich in natural resources and that is in a remarkable growth phase, namely the KSA. To analyze the short- and long-term relationship between the variables in the study, we used the NARDL model. However, this method required us to go through several stages; the first of which was to check the stationarity of our variables, relying on the ADF, PP, and Zivot and Andrews tests. The results of the three tests proved that the variables are all differenced stationary (DS) processes and are integrated of order 1 at the 1% threshold. Secondly, we verified the existence of a long-term relationship between the variables using the Bounds cointegration test. To analyze the asymmetry effect, we used the results derived from the long-term model describing the calculated coefficients of the positive and negative sums for the increase and reduction of the decomposed variables.

After checking the various stages, the long-term results of our NARDL model enabled us to draw the following conclusions: a positive shock to ECI has a positive and significant effect on the EFP, whereas a negative shock contributes to a reduction in the EFP. For the NRR variable, the results show that it has a negative and significant impact on the EFP in the case of a negative and positive shock. Indeed, a negative shock has a higher magnitude than a positive shock. In the short term, we found that a positive shock to ECI significantly and negatively affects the EFP, while a negative shock contributes to an increase in the EFP. Thus, we can conclude that the effect of EC persists in both the short and long terms, and hence, environmental sustainability is influenced by ECI.

To give more relevance to our results, the symmetric and asymmetric causality test was used. The result showed a one-way relationship ranging from EFP to negative NRR shocks (NRR^{-}). In contrast, there are unidirectional relationships from positive NRR shocks (NRR^{+}) to EFP. These results show that NRR has a positive effect on EFP, depending on the environmental situation. Furthermore, the results also reveal a bidirectional relationship between positive and negative shocks to EC (ECI^{+}, ECI^{-}) and the EFP.

5.2. Policy Implications

The results of this study offer several important policy insights for Saudi Arabia's sustainable development agenda under Vision 2030. First, the finding that positive long-run shocks to ECI increase EFP, while negative shocks significantly reduce it, indicates that expanding economic complexity without environmental safeguards can intensify ecological pressure. Therefore, policies promoting diversification should prioritize environmentally efficient forms of complexity rather than indiscriminate industrial expansion. This implies directing diversification efforts toward less energy-intensive and cleaner sectors. Second, the presence of short-run and long-run effects of ECI on EFP, along with bidirectional causality between ECI shocks and EFP, suggests that environmental degradation and economic complexity influence each other dynamically. This reinforces the need for early integration of environmental standards within diversification strategies, rather than corrective actions applied only after environmental damage occurs. Third, the results reveal that both positive and negative shocks to NRR reduce EFP, with stronger effects from negative shocks, and unidirectional causality running from NRR shocks to EFP. This indicates that reduced reliance on resource extraction lowers ecological pressure, while increases in resource rents may reduce EFP only if revenues are managed efficiently. Consequently, policies should focus on using natural resource rents to support environmental investments, rather than expanding extraction activities.

Overall, the empirical evidence implies that sustainable development in Saudi Arabia depends not on increasing economic complexity or resource rents per se, but on managing their asymmetric environmental effects over time. This highlights the importance of evidence-based, targeted policies aligned with the observed dynamics rather than broad, growth-oriented strategies.

5.3. Limitations and Future Research

This study offers novel insights into the asymmetric relationship between economic complexity, natural resource rents, and the ecological footprint in Saudi Arabia using the NARDL approach. However, several limitations should be acknowledged. First, the use of aggregated ecological footprint data may conceal sectoral or regional variations in environmental pressures. Second, potential endogeneity issues could arise from omitted variables or reverse causality between the ecological footprint and key explanatory variables. For future research, extensions could include applying the Quantile Autoregressive Distributed Lag (QARDL) model to capture potential heterogeneous effects across different levels of the ecological footprint. Additionally, incorporating renewable energy consumption, institutional quality, or green technology adoption could enrich the analysis and provide more policy-relevant insights for sustainable development under Saudi Arabia's Vision 2030 agenda.

Author Contributions

Conceptualization, M.A., H.A., M.E., Z.G. and R.A.E.A.K.; methodology, M.A.; software, M.A.; validation, M.A., H.A., M.E., Z.G. and R.A.E.A.K.; formal analysis, M.A.; investigation, M.A.; resources, M.A.; data curation, M.A.; writing—original draft preparation, M.A.; writing—review and editing, M.A.; visualization, M.A.; supervision, M.A.; project administration, M.A.; funding acquisition, M.A. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data used in this study can be provided upon request.

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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