



Unveiling the Path to Environmental Sustainability in Saudi Arabia: The Role of Geopolitical Risks and Corruption

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ABSTRACT

Environmental sustainability is a critical global challenge for Saudi Arabia. While geopolitical risks and corruption significantly impact sustainability, their specific effects within a single-country context remain underexplored. To address this gap, this study uses dynamic autoregressive distributed lag simulations and kernel-based regularized least squares estimation to examine the influence of geopolitical risk, corruption, natural resource rents, and economic growth on Saudi Arabia's environmental sustainability from 1990 to 2021. The findings reveal that geopolitical risk negatively affects environmental sustainability in the short term, but Saudi Arabia's economic resilience and policy responses mitigate its long-term impact. Conversely, corruption consistently deteriorates environmental sustainability by increasing carbon emissions and widening the short- and long-term ecological footprint. Additionally, economic growth and natural resource rents exacerbate environmental degradation. These findings underscore the urgent need for Saudi policymakers to strengthen anti-corruption measures, promote economic diversification, and reduce dependence on natural resource rents to achieve long-term environmental sustainability.

Keywords: Environmental Sustainability, Geopolitical risk, Corruption, Dynamic ARDL Model, Saudi Arabia.

INTRODUCTION

Environmental sustainability has become one of the most pressing global priorities of the 21st century, reflecting the urgent need to address the multifaceted challenges driven by climate change, ecological degradation, and resource depletion (Arora et al. 2018). As stated in the United Nations Sustainable Development Goals, sustainable development strongly emphasizes environmental objectives to ensure the planet's long-term health. Key goals include combating climate change (SDG 13), conserving marine resources (SDG 14), and protecting terrestrial ecosystems (SDG 15) to address critical environmental challenges, including biodiversity loss, pollution, and resource depletion. These objectives emphasize the importance of transitioning to sustainable consumption and production patterns (SDG 12), promoting renewable energy (SDG7), adopting climate-resilient practices, and mitigating environmental risks. However, achieving these goals requires navigating a complex landscape of structural barriers and systemic risks undermining progress. Among these challenges, geopolitical risks and corruption stand out as significant yet underexplored factors influencing the trajectory of environmental sustainability, particularly in resource-dependent nations.

Geopolitical risks—such as conflicts, political instability, trade tensions, and territorial disputes, can undermine environmental sustainability (Sweidan (2023)). These risks disrupt international cooperation, destabilize resource management systems, and often prioritize short-term political or economic benefits over long-term ecological preservation. For instance, geopolitical tensions in energy-exporting regions such as the Middle East often lead to the unregulated exploitation of natural resources to secure strategic advantages, thereby accelerating environmental degradation (Khezri et al. 2023). Trade conflicts over renewable energy technologies have disrupted global supply chains and hindered the diffusion of clean energy (Ghosh 2016).

Resource conflicts and energy security concerns further intensify the environmental challenges associated with geopolitical risks. Countries involved in territorial disputes over valuable resources, such as oil and natural gas, frequently use environmentally destructive practices to assert control and maximize short-term gains.

Moreover, increased militarization of resource-rich areas leads to ecological destruction and diverts critical resources from sustainability initiatives (Mohammedi et al. 2025). The interaction between geopolitical instability and environmental policies is mainly pronounced in the context of global climate agreements, where regional conflicts and competing national interests undermine collective action. However, an alternative perspective presents a counterintuitive argument, suggesting that geopolitical risks may mitigate environmental degradation under specific circumstances by influencing economic activities and industrial operations. This perspective suggests that geopolitical uncertainties may slow economic growth, particularly in resource-intensive and high-emission sectors, ultimately limiting environmental harm. For instance, Kızılkaya et al. (2024) show that increasing geopolitical risks in Turkey led to decreased carbon emissions due to a slowdown in industrial production and reduced economic output in pollution-heavy industries. Similarly, Li et al. (2024) demonstrated that geopolitical tensions in the BRICS countries have led to policy orientation and economic activity changes, indirectly contributing to improved ecological outcomes in some contexts.

Corruption presents another obstacle to environmental sustainability by undermining the institutional integrity necessary for effective environmental governance. It takes various forms, including the misappropriation of funds allocated to sustainability projects, the weakening of environmental regulations, and the facilitation of illegal activities such as deforestation, overfishing, and unregulated mining (Transparency International 2022). These corrupt practices deplete natural resources and lead to substantial ecological degradation, particularly in nations with high levels of resource dependence and weak institutional frameworks. In resource-dependent economies, corruption often exacerbates the environmental consequences of resource extraction by allowing companies to bypass environmental standards and regulations. For instance, oil, natural gas, and minerals extraction are frequently associated with ecological harm due to weak regulatory oversight and a lack of accountability (Yuan & Xiang 2018). This challenge is intensified by corruption, which not only reduces the environmental gains from renewable energy but also amplifies the adverse effects of fossil fuel consumption (Sinha et al. 2019). Moreover, the effectiveness of environmental regulations is significantly compromised without robust anti-corruption efforts (Zhou & Li 2021).

Environmental sustainability has become a global imperative, especially for resource-dependent economies that face the dual challenge of maintaining economic growth while mitigating ecological degradation. Achieving sustainable development is even more complex for countries facing geopolitical and institutional challenges. As a leading oil producer, Saudi Arabia's economy strongly relies on fossil oil, making the transition toward sustainability both urgent and challenging. Its ambitious Vision 2030 underlines a commitment to diversifying the economy, promoting renewable energy, and addressing environmental challenges. However, achieving these goals is complicated by Saudi Arabia's location in a geopolitically volatile region, where conflicts, trade disputes, and shifting alliances shape its policy environment. Regional tensions, such as those involving neighboring countries or broader international energy transitions, directly impact Saudi Arabia's ability to allocate resources and prioritize environmental initiatives. These geopolitical risks strain its capacity to implement sustainability reforms and affect its collaboration in global environmental agreements. At the same time, corruption within governance structures remains a significant barrier to achieving sustainability goals. While Saudi Arabia has undertaken significant reforms to combat corruption, such practices can still undermine institutional effectiveness, weaken regulatory enforcement, dilute the impact of environmental programs, and often prioritize short-term economic benefits over long-term sustainability. This dual challenge of geopolitical risks and corruption makes Saudi Arabia a significant case for examining how these factors affect environmental sustainability.

In this regard, this research seeks to explore the combined impacts of geopolitical risk and corruption on environmental sustainability in Saudi Arabia while considering natural resource rents and economic growth. This study is motivated by the ongoing lack of consensus among researchers regarding the connection between geopolitical risk, corruption, and environmental sustainability. The choice of Saudi Arabia is motivated by its strategic importance in the global energy sector, its particular geopolitical position, and its ambitious reform initiatives under Vision 2030, and by the lack of studies on the effect of geopolitical risk and corruption on environmental sustainability in this context.

This research enhances the environmental literature in three significant aspects: First, most recent research focuses on single-country analysis (Hunjra et al. 2024), often overlooking country-specific economic, social, and geopolitical factors that significantly shape environmental outcomes. By examining Saudi Arabia, this study addresses this gap and deeply analyzes how geopolitical risk and corruption affect environmental sustainability within a single-nation context. Second, this study attempts to be the first to explore the role of geopolitical risk and corruption in Saudi Arabia's environmental sustainability. Third, from an empirical perspective and compared to existing research, this paper adopts a novel dynamic autoregressive distributed lag (ARDL) simulation approach and a kernel-based regularized least squares (KRLS) technique. The dynamic ARDL simulations accurately model both positive and negative shifts of independent variables over the short and long run. They also capture asymmetries in the inter-variable relationships. In addition, a KRLS technique was employed to overcome the limitations of the traditional method by providing flexible, non-linear modeling possibilities and improving the robustness of the results. Finally, our work adds to the more extensive discussion on sustainable development in natural resource-rent-dependent economies by providing pertinent information to stakeholders and policymakers in Saudi Arabia and other similar contexts. This work is organized as follows: Section 2 focuses on the literature, Section 3 outlines the methodology, and Section 4 presents the empirical findings. Section 5 concludes with policy recommendations.

LITERATURE REVIEW

Geopolitical Risks and Environmental Sustainability

In the past few years, geopolitical risk (GPR) has emerged as a key factor shaping environmental sustainability; however, empirical studies have presented divergent views on its impact. The first view of studies argues that GPR is positively associated with environmental degradation, suggesting that heightened GPR may hinder environmental policies and encourage dependence on carbon-intensive energy sources. For instance, Hashmi et al. (2022) investigated the relationship between GPR and CO₂ emissions worldwide from 1970–2015. The main results indicate that geopolitical risk (GPR) has a dual impact on global CO₂ emissions. Higher GPR significantly reduces emissions in the short term, as political tensions, conflicts, or threats disrupt industrial production and energy consumption, leading to a temporary slowdown in economic activity. However, in the long run, an increase in GPR ultimately leads to higher emissions, as prolonged instability discourages investment in research, innovation, and clean technologies, forcing economies to continue relying on older, more carbon-intensive production methods. Pata et al. (2023) investigate how economic policy uncertainty (EPU), geopolitical risk (GPR), urbanization, and income affect renewable energy investments in G7 countries. Their findings reveal that while GDP positively influences renewable energy investments, both EPU and GPR negatively affect investments in renewable energy in G7 countries. The work underlines the importance of reducing uncertainty and geopolitical tensions to promote clean energy investments. Chen et al. (2023) explored the impact of geopolitical risk, natural resource rents, renewable energy consumption, and economic growth on CO₂ emissions in 38 developing and industrialized nations from 1970 to 2021. The study revealed that rising geopolitical risks increase CO₂ emissions, with the effect being further intensified by natural resource rents. This outcome can be attributed to increased geopolitical tensions and inefficient use of natural resources, which may undermine global efforts toward sustainability and hinder the adoption of renewable energy in both developing and developed nations. In the case of 25 OECD countries, Ding et al. (2023) explore the effect of GPR on CO₂ emissions. Their findings indicate that heightened GPR increases carbon emissions, mainly due to the intensified extraction and use of mineral resources, which are often carbon-intensive processes. This suggests that geopolitical tensions may hamper environmental sustainability efforts by driving activities that elevate carbon emissions. Similarly, Li, Z. (2023) used the Bootstrapped ARDL model to explore geopolitical risk's impact on China's environmental sustainability from 1995 to 2020. The outcomes suggest that heightened GPR harms environmental sustainability and increases environmental degradation. This suggests that geopolitical tensions can hinder China's sustainability efforts.

Wang, W. et al. (2024) argue that GPR adversely affects environmental sustainability in selected Asian countries. They indicate that higher levels of geopolitical risk lead to greater reliance on non-renewable energy, thereby hindering efforts to decrease emissions. Also, Luo et al. (2024) explored the impact of GPR on consumption-based carbon dioxide emissions in 27 countries from 1990 to 2020. The outcomes demonstrate that GPR increases environmental degradation, particularly in countries with higher consumption-based carbon dioxide emissions, suggesting that nations already emitting large amounts of carbon are more susceptible to the environmental impacts of geopolitical risks. More recently, Mohammadi et al. (2025) examined the impact of GPR on environmental sustainability in developed and developing countries. They find that GPR increases environmental degradation, mainly by disrupting energy markets and reducing investments in renewable energy projects. Their study

emphasizes that the adverse environmental effects of GPR are more pronounced in developing economies, where energy transitions are slower due to economic and political instability.

The second view of research suggested that geopolitical risk is negatively associated with environmental degradation. Chu et al. (2022) found that the long-run ecological effects of GPR are beneficial in E7 economies. They attributed the negative relationship to a decline in consumption and investment caused by high GPR. According to Hasnain et al. (2022), geopolitical risks contribute to a decrease in long-term environmental degradation. These risks slow economic activity, reduce industrial output, and lower fossil fuel consumption. Uddin et al. (2023) find that geopolitical risks can positively impact sustainability efforts by prompting governments and businesses to adopt cleaner energy policies and reduce CO₂ emissions in BRICS economies. Similarly, research by Li et al. (2024) found that geopolitical instability can limit economic activity and thus reduce ecological pressures. Focusing on G-20 nations, Balsalobre-Lorente et al. (2024) examine the influence of GPR on ecological footprint, CO₂ emissions, and carbon footprint. The results indicate that GPR reduces all three environmental parameters in the long run. However, these environmental benefits linked to geopolitical disruptions stem from economic contraction rather than sustained political progress. Focusing on Italy over the period 1997-2019, Nawaz et al. (2023) study the influence of GPR on CO₂ emissions. Their results suggest that GPR has a mitigating effect on CO₂ emissions. The authors attribute this finding to economic slowdowns and the Pope's distinctive role in promoting sustainability during times of instability caused by high GPR. Kızılkaya et al. (2024) explored Turkish data from 1985–2019 and showed that GPR is negatively associated with carbon emissions in the long run. This mitigating effect occurs because an increase in GPR tends to disrupt economic activities, particularly in emission-intensive industries, thereby reducing energy consumption and CO₂ emissions related to production. In the same case, Saadaoui, et al. (2024) found that GPR decreases carbon emissions in the long run, likely due to its impact on fossil fuel demand. Specifically, heightened geopolitical risk tends to influence fossil fuel prices, particularly oil, which makes the consumption and production of alternative and accessible energies more important.

Research also indicates that an asymmetric link between GPR and environmental sustainability has been documented in the literature. Zhao et al. (2021) explored the asymmetric effect of GPR on CO₂ emissions in BRICS economies from 1985 to 2019. The outcomes indicate that increased GPR reduces Russia's and South Africa's emissions. In contrast, decreasing GPR lowers emissions in India, China, and South Africa but raises emissions in Russia. The authors also concluded that these asymmetries are mainly in terms of magnitude rather than direction. Shifting the focus to BRICST countries, Syed et al. (2022) show that GPR significantly raises CO₂ emissions, especially in higher-emitting nations, where geopolitical tensions disrupt clean energy transitions and increase reliance on traditional energy sources. The work further reveals that the impact of GPR is more pronounced at higher emission levels, highlighting the threat geopolitical instability pose to environmental sustainability in heavily industrialized nations. In the same line, Ben Abdallah et al. (2024) sought to explore the role of GPR on renewable energy use in selected industrial economies. They found that higher GPR thresholds encourage investments in clean energy, suggesting that industrial economies respond to geopolitical challenges by shifting toward renewable energy. However, geopolitical risks also slow energy transitions in less adaptable economies, contributing to environmental degradation.

Corruption and Environmental Sustainability

Numerous studies argue that corruption hampers formulating and enforcing environmental policies, thereby worsening environmental conditions. Notably, research by Akalin et al. (2021) indicates that in newly industrialized countries, corruption adversely affects environmental quality by facilitating regulatory evasion, undermining the enforcement of environmental laws, and enabling harmful activities in the informal sector. Similarly, studies by Chen et al. (2018), Pei et al. (2021), and Zhou et al. (2019) regarding China corroborate these findings.

Moreover, Hao, Gai, and Wu (2020) highlighted that corruption undermines environmental policies and weakens institutional frameworks, leading to inefficiencies in energy consumption and increased environmental degradation. This suggests that addressing resource misallocation and corruption could substantially improve energy efficiency and contribute to China's green development goals. Similarly, Hao et al. (2021) find that corruption directly affects pollution while environmental decentralization improves air quality only under low corruption levels and strong governance frameworks in China. Shifting the focus to 17 MENA countries from 1984 to 2018, Khalfaoui et al. (2023) examine the connection between corruption and environmental quality. The empirical findings indicate that corruption worsens environmental degradation by weakening environmental policies and increasing CO₂ emissions. Along the same lines, Tawiah et al. (2024) investigated the effect of corruption on green growth in 123 countries between 2000 and 2017. They find that corruption hinders green growth, indicating that countries with high levels of corruption are less capable of mitigating the environmental consequences of rapid economic growth. Further analysis suggests that no country is exempt from the harmful environmental effects of corruption. Likewise, Li et al. (2024) revealed that controlling corruption improves the ecological environment, particularly in countries with poor environmental quality. Hwang et al. (2024) investigate

the effect of corruption on environmental quality within Commonwealth of Independent States (CIS) countries. The findings underscore that higher levels of corruption degrade environmental quality, mainly by increasing CO₂ emissions and weakening the effectiveness of environmental regulations. Li et al. (2025) examine the impact of corruption on environmental quality in Costa Rica from 1990 to 2020. The study finds that corruption has a significant short-term negative effect on environmental quality, which declines over time. The findings suggest that although corruption initially worsens environmental degradation, its adverse effects may diminish as governance structures improve.

Natural Resource Rent and Environmental Sustainability

The empirical literature is mainly divided into two views. Some research suggests that natural resource rents (NRT) harm environmental sustainability. For instance, Zuo et al. (2022) examine the impact of natural resource rents, financial development, and technological innovations on the ecological footprint in 90 countries involved in the Belt and Road Initiative (BRI) from 1991 to 2018. Their findings suggest that natural resource rents have a significant negative impact on the ecological footprint. This result can be explained by the heavy dependence on the extraction of resources such as oil, gas, coal, and minerals leads to greater energy consumption, higher industrial emissions, and intensified ecological degradation in these economies. Focusing on G7 countries, Gyamfi et al (2022) examined the effects of natural resource rents and renewable and fossil fuel energy consumption on environmental quality. Their results revealed that natural resources often lead to greater environmental degradation, supporting the hypothesis that natural resource rent is mainly channeled towards sources of increased productivity, which aggravates environmental degradation. Zambrano-Monserrate (2023) found that, in 24 high-pollution countries, oil rents have a more substantial adverse effect on the environmental footprint than mineral and natural gas rents. Using a Quantile autoregressive distributed lag model, Huang et al. (2023) examined the dynamic link between natural resource rents, financial development and urbanization on carbon emissions in the United States over the period 1995-2015. Their findings reveal that higher natural resource rents, urbanization, and financial development are putting more environmental pressure on the U.S. economy. Likewise, Irfan et al. (2025) examine the impact of natural resource rents on carbon emissions in BRICS countries, taking into account additional factors such as agriculture, forestry, fisheries, ICT goods trade, green technology and innovation, economic growth, and government effectiveness. The results show that all factors, except government effectiveness, are associated with increased CO₂ emissions, underscoring the environmental burden of economic and sectoral activities in these countries.

Other research has shown that NRT mitigate environmental degradation. Safdar et al. (2022) explored six selected South Asian countries between 1996 and 2020 and found that Although NRT are typically linked to higher greenhouse gas (GHG) emissions, this negative impact can be significantly reduced in the presence of good governance. Their results demonstrate that strong institutional quality and effective governance not only help lower emissions directly but also weaken the harmful environmental effects associated with resource dependence. Arslan et al. (2022) investigate how good trade and manufacturing value-added moderate the dynamic link among NRT, environmental sustainability, and economic growth in China from 1970 to 2016. Their findings suggest that natural resource rents enhance environmental sustainability, albeit at the cost of slower economic growth. In contrast, financial development, urban population growth, and good trade contribute to increased environmental degradation, underscoring the trade-offs between economic expansion and environmental protection. Using the Method of Moments Quantile Regression, Hacıımamoğlu and Cengiz (2023) investigate how renewable energy consumption and natural resource rents affect environmental degradation in the ASEAN-5 countries within the framework of the Environmental Kuznets Curve hypothesis. They found that NRTs decrease environmental degradation, suggesting that resource revenues are being used in environmentally beneficial ways in these countries. Similarly, natural resource rents contribute to sustainability by providing financial means that, when managed effectively, can fund green technologies and environmental initiatives, thereby reducing ecological degradation over time in Gulf Cooperation Council countries (Salim et al. 2024).

Economic Growth and Environmental Sustainability

Economic growth is frequently seen as both a driver of environmental degradation and a potential solution. The pioneering work of Grossman G. Krueger A. (1991), who studied the environmental Kuznets curve (EKC) assumption, reveals the validity of an inverted U-shaped economic growth-environmental degradation nexus. This hypothesis suggests that environmental degradation worsens with increasing economic growth until it reaches a threshold and then declines with economic growth beyond that threshold. For instance, Udeagha and Muchapondwa (2022) studied the effect of economic growth on environmental degradation in South Africa from 1960 to 2020 and confirmed the presence of the EKC assumption.

Additionally, Awan and Azam (2022) explored the EKC hypothesis for five major G-20 countries from 1993 to 2017, by incorporating technological development, financial development, energy consumption, and social

globalization. The outcomes confirm an N-shaped curve, indicating that emissions initially rise, then fall and eventually increase again at higher income levels. Focusing on the top ten countries in the world in terms of carbon, material, and ecological footprint from 1990 to 2017, Villanthenkodath et al. (2024) examine the link between economic growth and environmental quality. They confirm an N-shaped Environmental Kuznets Curve for carbon footprints while revealing an inverted N-shaped for ecological footprints. Likewise, Wang, Q. et al. (2024) found the same result in the context of 214 countries. Wang, S. et al. (2024) supported both the EKC and LCC hypotheses in BRICS countries. Specifically, the EKC hypothesis is confirmed for CO₂ emissions, which initially rise with income and then decline. In contrast, the LCC hypothesis is supported by the load capacity factor, which initially decreases and then improves as income increases, indicating a turning point where green technologies and ecological awareness become more influential.

Research Gaps

In summary, the empirical studies on the link between geopolitical risk, corruption, and environmental sustainability highlight significant findings but reveal some gaps. One such notable gap is the limited amount of research that examines these two critical factors together, as they are often studied separately. Furthermore, this study addresses the scarcity of literature on the role of GPR and corruption on environmental sustainability in the Saudi Arabian context. It explores how these factors influence Saudi Arabia's efforts to shift from an economy dependent on fossil fuels to one driven by renewable energy. Consequently, this research aims to fill these gaps and enhance the existing literature with a more thorough analysis.

METHODOLOGY

Data and Variables

This study covers the annual-time series dataset for Saudi Arabia from 1990 to 2021. The model uses carbon intensity (CO₂ per exajoule) and ecological footprint (global hectares per capita) as indicators of energy transition. The carbon intensity (CI) data is obtained from the U.S. Energy Information Administration (EIA). Carbon intensity refers to the amount of carbon dioxide (CO₂) emitted into the atmosphere per unit of energy consumed. This metric is used to evaluate the environmental impact of energy production and consumption, particularly in the context of energy systems and carbon emissions. Lower carbon intensity indicates a more efficient or cleaner energy source with fewer emissions. In comparison, higher carbon intensity reflects greater reliance on carbon-intensive energy sources such as coal, oil, or natural gas.

In contrast, ecological footprint (EFP) data is collected from the Global Footprint Network. The independent variables include geopolitical risk (GPR) and control of corruption (CC) as the main variables of interest. The Geopolitical Risk Index (GPR) is derived from the methodology developed by Caldara and Iacovello (2022). The Geopolitical Risk Index is a quantitative measure that tracks the frequency of articles related to geopolitical tensions in major international newspapers. This index reflects the percentage of news articles discussing Peace Threats, Military Buildups, terrorism, and international crises. In contrast, the corruption data is sourced from the International Country Risk Guide (ICRG). It is assessed on a scale of 0 to 6, where higher values indicate stronger governance and lower levels of corruption.

Additionally, natural resource rents (as a percentage of GDP) and real gross domestic product per capita (measured in constant 2015 USD) are included as control variables, justified by their correlation with energy transition in Saudi Arabia. Resource-dependent economies often face challenges transitioning to sustainable energy due to their reliance on fossil fuel exports and the "resource curse" dynamic. Saudi Arabia's heavy dependence on oil revenue significantly influences its energy policy. Incorporating natural resource rents as a control variable allows us to isolate the impact of geopolitical risk and corruption from the structural effects of resource dependency on energy transition efforts. Similarly, real GDP is closely linked to economic activities and energy consumption, major contributors to greenhouse gas emissions. Higher levels of economic development are often associated with increased industrialization, urbanization, and energy consumption, which can challenge the energy transition. Including economic growth as a control variable, we can shed light on the consequences of the economic progress of the energy transition in Saudi Arabia. The data on natural resource rents (%GDP) and GDP per capita (constant 2015 USD) are obtained from the World Bank (2023). The variables, abbreviations, series definitions, and data sources are detailed in Table 1.

Table 2 summarizes the descriptive statistics for the data sample from 1990 to 2021, including the means, maximum and minimum values, standard deviations, and normality test results. The Carbon Intensity (LCI) exhibits a relatively narrow range, with values spanning from 3.956 to 4.103, indicating a stable pattern throughout the study period. This limited variability, combined with a mean of 4.020, suggests minimal fluctuations in carbon intensity over time. Ecological Footprint (LFP) shows a wider range, with values ranging from 0.858 to 1.924,

reflecting substantial differences in ecological impact over time. Geopolitical Risk (GPR) varies from 0.057 to 0.871, highlighting extreme events during the sample period. Control of Corruption data ranges from 2 to 3.11, indicating a moderate fluctuation in corruption control levels over the study period. Natural Resource Rent (LNRT) spans from 2.851 to 4.007, underlining a moderate variation in the economic returns from natural resources. Gross Domestic Product (LGDP) spans from 9.659 to 9.925, emphasizing a relatively narrow range that indicates consistent economic performance across the study period. These statistics collectively illustrate the dynamic landscape of environmental, economic, and geopolitical factors in the Saudi Arabia dataset, highlighting both the consistency and variability among the variables.

Table 1. Variables, Abbreviations, Definitions, and Data Sources

Variables	Abbreviation	Definitions	Source
Carbon Intensity	LCI	carbon intensity (CO ₂ per exajoule)	U.S. Energy Information Administration (EIA)
Ecological Footprint	LFP	ecological footprint (global hectares per capita)	Global Footprint Network
Geopolitical Risk	GPR	Geopolitical Risk Index	Caldara & Iacoviello (2022) https://www.policyuncertainty.com/gpr.html .
Corruption	CC	Control of corruption	International Country Risk Guide (ICRG)
Natural resources rents	LNRT	Total natural resources rents (% of GDP)	WDI (2023)
GDP per capita	LGDP	Gross domestic product per capita	Total natural resources rents (% of GDP)

Table 2. Descriptive Statistics and Correlation Matrix

Variables	LCI _{CI}	LFP	GPR	LNRT	LGDP	CC
Descriptive statistics						
Mean	4.020	1.463	0.230	3.526	9.825	2.391
Median	4.009	1.503	0.167	3.508	9.815	2.000
Maximum	4.103	1.924	0.871	4.007	9.925	3.110
Minimum	3.956	0.858	0.057	2.851	9.659	2.000
Std.Dev.	0.047	0.322	0.189	0.297	0.070	0.439
Skewness	0.413	-0.476	2.086	-0.206	-0.288	0.938
Kurtosis	1.681	1.998	7.320	2.213	2.263	2.169
Correlation Matrix						
LCI	1.000					
LFP	-0.839	1.000				
GPR	0.210	-0.090	1.000			
LNRT	-0.293	0.025	-0.012	1.000		
LGDP	-0.170	0.448	0.162	-0.279	1.000	
CC	-0.456	0.721	0.139	-0.494	0.525	1.000
Observations	32	32	32	32	32	32

Model Presentation

To investigate the impact of geopolitical risk and corruption on the energy transition, we applied the novel Dynamic Autoregressive Distributed Lag (DARDL) model proposed by Jordan and Philips (2018). This approach offers several key advantages, making it a robust choice for time-series analysis. First, it supports variables with mixed orders of integration (I(0) and I(1), which allows for comprehensive modeling without the need to pre-differentiate or exclude data. Second, the model effectively captures short- and long-run dynamics, distinguishing immediate impacts from long-term equilibrium relationships. Its robust cointegration analysis allows the study of long-run relationships even without perfect cointegration. Third, by including lagged values of the dependent variable, the model minimizes endogeneity concerns, ensuring more reliable parameter estimates. Finally, it remains efficient even for small sample sizes, making it particularly suitable for studies with limited data.

Zivot-Andrews structural break unit root test. Before implementing the dynamic ARDL approach, we need to determine each variable's stationarity and order of integration. Besides traditional stationarity tests such as the Augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP), we also used the Zivot and Andrews test (1992) with a single structural break. The Zivot-Andrews test is a statistical method used to detect the unit root in a time series while accounting for the possibility of a single structural break in the data. Unlike traditional unit root tests,

which may fail to reject the null hypothesis of a unit root when structural breaks are present, the Zivot-Andrews test addresses this limitation by identifying and incorporating an endogenous breakpoint, making it more robust for analyzing time-series data with potential structural lags.

ARDL Bounds Testing for Cointegration. We use the ARDL bounds test pioneered by Pesaran et al. (2001) to examine the cointegration relationship among variables. The estimated models are outlined as follows:

Model 1:

$$\Delta LCI_t = \alpha_0 + \sum_{i=1}^{p_1} \alpha_{1i} \Delta LCI_{t-i} + \sum_{i=1}^{p_2} \alpha_{2i} \Delta GPR_{t-i} + \sum_{i=1}^{p_3} \alpha_{3i} \Delta CC_{t-i} + \sum_{i=1}^{p_4} \alpha_{4i} \Delta LNRT_{t-i} + \sum_{i=1}^{p_5} \alpha_{5i} \Delta LGDP_{t-i} + \varphi_1 LCI_{t-1} + \varphi_2 GPR_{t-1} + \varphi_3 CC_{t-1} + \varphi_4 LNRT_{t-1} + \varphi_5 LGDP_{t-1} + \varepsilon_{1t} \tag{1}$$

Model 2:

$$\Delta LFP_t = \alpha_0 + \sum_{i=1}^{p_1} \alpha_{1i} \Delta LFP_{t-i} + \sum_{i=1}^{p_2} \alpha_{2i} \Delta GPR_{t-i} + \sum_{i=1}^{p_3} \alpha_{3i} \Delta CC_{t-i} + \sum_{i=1}^{p_4} \alpha_{4i} \Delta LNRT_{t-i} + \sum_{i=1}^{p_5} \alpha_{5i} \Delta LGDP_{t-i} + \varphi_1 LCI_{t-1} + \varphi_2 GPR_{t-1} + \varphi_3 CC_{t-1} + \varphi_4 LNRT_{t-1} + \varphi_5 LGDP_{t-1} + \varepsilon_{2t} \tag{2}$$

Where ΔLCI , ΔLFP , ΔGPR , ΔCC , $\Delta LNRT$, $\Delta LGDP$ denote the first difference operator of the variables; α and φ represent the coefficients of the lagged variables in the short- and long-term. ε being the error terms, and $t - i$ represents the optimal lag length, determined using the selected information criterion. To assess the presence of a long-term relationship among the variables, two hypotheses will be tested: $H_0 : \vartheta_1 = \vartheta_2 = \vartheta_3 = \vartheta_4 = \vartheta_5 = 0$; against $H_1 : \vartheta_1 \neq \vartheta_2 \neq \vartheta_3 \neq \vartheta_4 \neq \vartheta_5 \neq 0$. We applied the modified Pesaran, Shin, and Smith (PSS) bounds test to accept or reject the null hypothesis, with Kripfganz and Schneider (KS) critical values and approximate p-values. The F-statistic is compared to the critical values for $I(0)$ and $I(1)$. If the F-statistic exceeds the upper bound (1), we reject the null hypothesis and confirm the presence of cointegration among the variables. Conversely, if the F-statistic is less than the lower critical value $I(0)$, we accept the null hypothesis, indicating the absence of cointegration. However, the results are inconclusive if the F-statistic falls between the lower and upper critical values. If the cointegration relationship is established between the variables, we proceed to estimate a long-run ARDL model, specified as follows:

$$\Delta LCI_t = \partial_0 + \sum_{i=1}^{q_1} \theta_1 LCI_{t-i} + \sum_{i=1}^{q_2} \theta_2 GPR_{t-i} + \sum_{i=1}^{q_3} \theta_3 LCC_{t-i} + \sum_{i=1}^{q_4} \theta_4 LNRT_{t-i} + \sum_{i=1}^{q_5} \theta_5 LGDP_{t-i} + \varepsilon_{1t} \tag{3}$$

$$\Delta LFP_t = \partial_0 + \sum_{i=1}^{q_1} \theta_1 LFP_{t-i} + \sum_{i=1}^{q_2} \theta_2 GPR_{t-i} + \sum_{i=1}^{q_3} \theta_3 LCC_{t-i} + \sum_{i=1}^{q_4} \theta_4 LNRT_{t-i} + \sum_{i=1}^{q_5} \theta_5 LGDP_{t-i} + \varepsilon_{2t} \tag{4}$$

In the short term, the error correction model (ECM) is specified as follows:

$$\Delta LCI_t = \sigma_0 + \sum_{i=1}^{q_1} \omega_1 \Delta LCI_{t-i} + \sum_{i=1}^{q_2} \omega_2 \Delta GPR_{t-i} + \sum_{i=1}^{q_3} \omega_3 \Delta CC_{t-i} + \sum_{i=1}^{q_4} \omega_4 \Delta LNRT_{t-i} + \sum_{i=1}^{q_5} \omega_5 \Delta LGDP_{t-i} + ECT_{t-1} + \varepsilon_{1t} \tag{5}$$

$$\Delta LFP_t = \sigma_0 + \sum_{i=1}^{q_1} \omega_1 \Delta LFP_{t-i} + \sum_{i=1}^{q_2} \omega_2 \Delta GPR_{t-i} + \sum_{i=1}^{q_3} \omega_3 \Delta CC_{t-i} + \sum_{i=1}^{q_4} \omega_4 \Delta LNRT_{t-i} + \sum_{i=1}^{q_5} \omega_5 \Delta LGDP_{t-i} + ECT_{t-1} + \varepsilon_{2t} \tag{6}$$

Where ECT_{t-1} denotes the Error Correction Term for one period lagged and captures the speed of adjustment to attain long-run equilibrium in the next period. Before proceeding into dynamic ARDL simulations, we carried out several diagnostic tests to ensure the robustness of the models.

Novel Dynamic ARDL Simulations

Jordan and Philips (2018) introduced the novel dynamic ARDL simulation. This method enhances the traditional ARDL approach by allowing the estimation, simulation, and visualization of the impact of changes in explanatory variables on dependent variables while keeping other independent variables constant (Khan et al. 2019). This method captures both short-run adjustments and long-run equilibrium dynamics, offering a comprehensive view of variable interactions. To estimate the novel dynamic simulated ARDL model, the variables must be stationary at the order of integration I(1) or I(0) and cointegrated. The variables in this study were tested and found appropriate for the DARDL approach. The formulation of the Error Correction Model, as proposed, can be articulated through the model specification as follows:

$$\begin{aligned} \Delta LCI_t = & \partial_0 + \gamma_1 LCI_{t-1} + \rho_1 \Delta LCI_{t-1} + \gamma_2 GPR_{t-1} + \rho_2 \Delta GPR_{t-1} + \gamma_3 CC_{t-1} + \rho_3 \Delta CC_{t-1} + \gamma_4 LNRT_{t-1} \\ & + \rho_4 \Delta LNRT_{t-1} + \gamma_5 LGDP_{t-1} + \rho_5 \Delta LGDP_{t-1} + \pi ECT_{t-1} + \varepsilon_t \end{aligned} \quad (7)$$

$$\begin{aligned} \Delta LFP_t = & \partial_0 + \gamma_1 LFP_{t-1} + \rho_1 \Delta LFP_{t-1} + \gamma_2 GPR_{t-1} + \rho_2 \Delta GPR_{t-1} + \gamma_3 CC_{t-1} + \rho_3 \Delta CC_{t-1} + \gamma_4 LNRT_{t-1} \\ & + \rho_4 \Delta LNRT_{t-1} + \gamma_5 LGDP_{t-1} + \rho_5 \Delta LGDP_{t-1} + \pi ECT_{t-1} + \varepsilon_t \end{aligned} \quad (8)$$

Kernel-based Regularized Least Squares (KRLS)

This study used the Kernel-based Regularized Least Squares (KRLS) machine learning algorithm, developed by Hainmueller and Hazlett (2014), to ensure robust and reliable results. This method was selected for its unique ability to assess "partial derivatives", which quantify the marginal effects of each variable at every data point. Although average marginal effects can be estimated, the main objective of this study was to explore and relate the distribution of these effects with the results from the dynamic ARDL model. Additionally, KRLS is valued for its empirical properties, including stability, unbiasedness, and asymptotic normality, provided reasonable symmetry assumptions are met. These features make KRLS particularly suitable for analyzing complex interactions and dependencies in empirical research. The Gaussian kernel function used in KRLS is expressed as follows:

$$K(x, x') = \exp \frac{-\|x-x'\|^2}{\sigma}$$

Here $K(x, x')$ represents the Gaussian kernel, which measures the similarity between two input vectors x and x' . The term $\|x - x'\|^2$ denotes the squared Euclidean distance between the vectors, and σ is the bandwidth parameter, also referred to as the Gaussian kernel width or scale parameter.

Empirical Outcomes

Unit Root Test

The first step in the dynamic ARDL model involves establishing the order of integration for each variable. This is essential to confirm that the dependent variable exhibits first-difference integration before estimating the dynamic ARDL simulation bounds test. In addition to traditional unit root tests, this study uses the Zivot-Andrews test to detect the endogenous breakpoints within the time series. By identifying structural breaks, the Zivot and Andrews test addresses a common issue in economic and financial data, enhancing the robustness of the analysis. Table 3 presents the findings of the unit root tests for all series. The tests show that the Carbon intensity (LCI) and Ecological Footprint (LFP) are integrated at I(1), independently of the nature of the tests used, confirming the use of the dynamic ARDL simulation. Furthermore, the results indicate a mixed order of integration among the independent variables. More precisely, we can deduce that GPR is integrated with order zero (I(0)), while CC, LNRT, and LGDP are integrated with order one (I(1)).

Table 3. Results from Unit Root Tests

	ADF		PP		Zivot and Andrews's Structural Break	
	t-Statistic (with Intercept)	t-Statistic (trend and Intercept)	t-Statistic (with Intercept)	t-Statistic (Trend and Intercept)	t-Statistic	Break Year
CI	-1.561	-1.579	-1.545	-1.625	-3.281 (0)	2013
Δ CI	-5.230***	-5.282***	-5.225***	-5.503***	-5.864***(0)	2007
LFP	-1.781	-2.677	-1.757	-2.775	-3.705(0)	2000
Δ LFP	-6.603***	-6.598***	-7.871***	-9.140***	-8.446***(0)	2000
GPR	-4.441***	-4.389***	-4.441***	-4.859***	-4.453 (0)	2001
Δ GPR	-	-	-	-	-6.185***(0)	1996
LNRT	-2.335	-2.306	-2.335	-2.306	-4.578(2)	2015
Δ LNRT	-5.907***	-5.851***	-7.169***	-10.177***	-6.743***(1)	2009
LGDP	-1.400	-1.816	-1.495	-1.816	-3.334(0)	2011
Δ LGDP	-5.526***	-5.623***	-5.523***	-5.709***	-6.778***(0)	2003
CC	0.477	-1.490	0.448	-1.454	-3.701(0)	2010
Δ CC	-4.911***	-5.185***	-4.888***	-5.694***	-6.078***(0)	2010

Note: ***, **, * represent respective 1%, 5%, and 10% significance levels, Δ is the first difference. (.) in parenthesis is the Lag order.

After meeting the condition of unit root tests, we proceed to select the optimal lag length that minimizes sequential modified test (LR), Final Prediction Error (FPE), Akaike information criterion (AIC), Schwarz Bayesian information criterion (SC), and Hannan-Quinn criterion (HQ). The results indicate that, regardless of the information criterion, the optimal lag is one (Table 4).

Table 4. Lag Length Criteria Results

	LogL	LR	FPE	AIC	HQ
Model 1					
0	178.610	NA	6.5 e-12	-11.576	-11.501
1	279.432	201.58*	4.2 E-14*	-16.628*	-16.628*
2	296.461	34.058	8.4E-14	-16.097	-16.097
Model 2					
0	83.609	NA	3.6E-9	-5.24	-5.165
1	172.066	17691*	4.5E-11*	-9.471*	-9.022*
2	189.187	34.242	1.1E-10	-8.945	-8.124

* Designates Lag Order Selected by the Criterion.

ARDL Bounds Test

Table 5 reports the outcomes of the modified Pesaran, Shin, and Smith (PSS) bounds cointegration test with Kripfganz and Schneider (KS) critical values. When carbon intensity (LCI) is used as the dependent variable, the estimated F-statistic is 5.226, while the t-statistic is -4.353, both surpassing the upper bound critical values (4.086 and -3.678) at the 5% significance level. This result is further confirmed by the approximate p-values of Kripfganz and Schneider, with $p < 0.05$, indicating the presence of a cointegration relationship. Similarly, when the ecological footprint (LFP) serves as the dependent variable, the estimated F-statistic (4.509) and the t-statistic (-4.125) also exceed the corresponding upper bound critical values, further confirming a cointegration relationship at the 5% significance level.

Table 5. ARDL Bounds Test

		Kripfganz and Schneider (2020) Critical Values and Approximate p-values								
		10%		5%		1%		p-value		
		I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
Model 1	F	5.226	2.143	3.381	2.667	4.086	3.961	5.803	0.003***	0.020**
	t	-4.35	-1.61	-3.25	-1.98	-3.67	-2.72	-4.54	0.000***	0.015**
Model 2	F	4.50	2.14	3.381	2.667	4.086	3.961	5.803	0.005***	0.020**

t	-4.12	-1.61	-3.25	-1.98	-3.67	-2.72	-4.54	0.000***	0.022**
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*, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Diagnostics Tests

Several diagnostic tests were carried out to confirm the consistency and reliability of the models. First, the Breusch-Godfrey LM test was employed to assess serial correlation in the residuals. The results presented in Table 6 indicate that both models are free from serial correlation. Second, heteroskedasticity in the residuals was assessed by Cameron and Trivedi's decomposition of the IM test, with the results in Table 7 confirming the absence of heteroskedasticity. Third, parameter stability was evaluated using the cumulative sum (CUSUM) test. As illustrated in Figure 2, the test statistic remains within the 95% confidence band, verifying the estimated coefficients' stability over time.

Table 6. Breusch-Godfrey LM Tests

Lags (p)	Model 1			Model 2		
	F	Df	p-value	F	Df	p-value
1	0.254	(1,21)	0.415	0.691	(1,22)	0.536
2	2.898	(2, 20)	0.707	0.352	(2, 21)	0.811
3	2.268	(3, 19)	0.148	1.995	(3, 20)	0.162
4	1.856	(4, 18)	0.241	1.508	(4, 19)	0.086

Table 7. Cameron & Trivedi's Decomposition of the IM-test

Source	Model 1			Model 2		
	Chi2	df	p-value	Chi2	df	p-value
Heteroskedasticity	24.98	27	0.575	30.00	29	0.414
Skewness	5.01	6	0.542	9.96	8	0.267
Kurtosis	1.10	1	0.293	0.22	1	0.639
Total	31.10	34	0.610	40.18	38	0.373

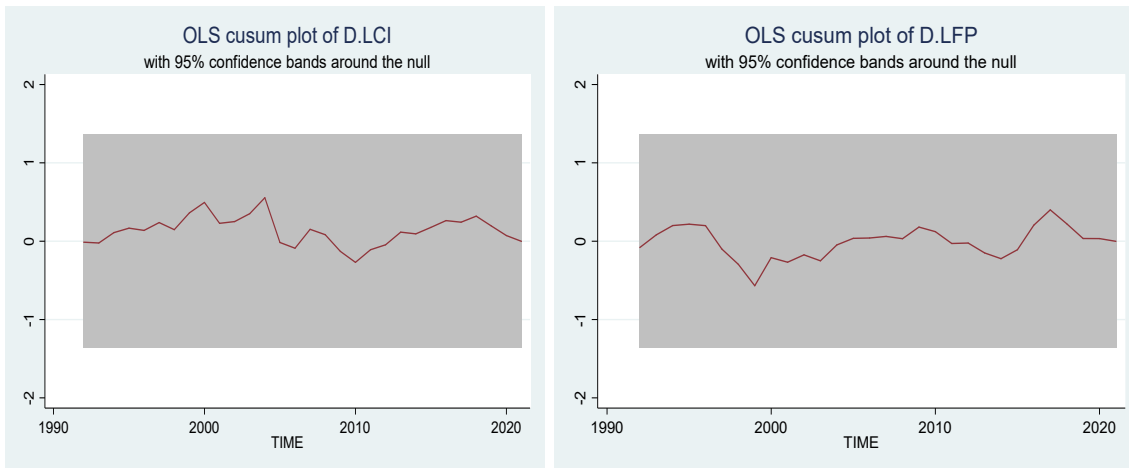


Figure 2. OLS CUSUM Plot for Parameter Stability

Dynamic ARDL Simulations Results

The outcomes obtained using the novel dynamic ARDL simulations in Table 8 provide a set of interconnected insights into the link between GPR and environmental sustainability in Saudi Arabia. The results indicate that GPR has a positive and statistically significant effect on carbon intensity in the short term at the 10% significance level, suggesting that geopolitical tensions prompt an immediate increase in fossil fuel consumption. This effect reflects Saudi Arabia's strategy of prioritizing energy security and economic stability during geopolitical uncertainties, often by intensifying fossil fuel production to stabilize revenues and market supply. Simultaneously, such conditions tend to delay the implementation of sustainability projects, given the reallocation of resources towards immediate economic imperatives. However, the long-term effect of GPR on environmental sustainability is statistically insignificant, suggesting that these effects can gradually dissipate or adjust over the long-term as markets and policies stabilize and countries adapt to new geopolitical circumstances. In Saudi Arabia, resilience and adaptability can explain the insignificant impact of GPR on long-term environmental sustainability. The long-term effects of geopolitical risk can be mitigated by Saudi Arabia's ongoing efforts under Vision 2030 to diversify the economy

and reduce dependence on oil revenues. Additionally, the country may be able to counteract the adverse effects of geopolitical tensions due to its dominating position in the global energy market, which would ensure that long-term environmental initiatives are primarily unaffected. These factors highlight Saudi Arabia's ability to protect its environmental program from prolonged geopolitical upheaval.

Moreover, the findings reveal a statistically significant negative relationship between corruption and environmental sustainability in both the short and long term. This suggests that corruption weakens efforts to improve environmental sustainability, measured by carbon intensity (LCI) and ecological footprint (LFP). Specifically, a 1% rise in control of corruption in Saudi Arabia reduces carbon intensity by 0.073% and 0.496% in the short- and long run, respectively. Additionally, it aggravates the ecological footprint by 0.390% in the short run and 0.496% in the long run. Consistent with Akalin et al. (2021), Khalfaoui et al. (2023), and Rongrong et al. (2024), corruption has been recognized as an important factor contributing to environmental degradation in developed and developing countries. Indeed, corruption hinders the application of environmental rules and the misallocation of resources, which worsens environmental degradation. Over time, these effects accumulate, leading to systemic challenges that hinder sustainable development. Therefore, corruption makes it more difficult to ensure a sustainable environment by compromising the necessary measures to protect biodiversity, reduce pollution, and preserve natural resources.

In response to these issues, Saudi Arabia has taken significant steps to reduce corruption and promote openness. One significant step in this regard is the creation of the Oversight and Anti-Corruption Authority (Nazaha), which is in charge of the country's anti-corruption initiatives. In order to strengthen public accountability, the government has implemented a whistleblower law to protect and encourage those who expose corrupt practices. Furthermore, Saudi Arabia has led internationally by establishing the Global Network of Anti-Corruption Law and the Riyadh Initiative.

In addition, the results show that natural resource rent contributes significantly to environmental degradation in Saudi Arabia's economy in both the short and long term. Specifically, a 1% rise in natural resource rent is projected to yield a 0.077% expansion in carbon intensity and a 0.404% rise in ecological footprint in the long run. This suggests that Saudi Arabia's heavy dependence on natural resource rents, mainly oil, significantly impacts environmental degradation over time. These findings align with those of Mahmood H. (2023), who found that natural resource rent increases the carbon intensity of oil emissions for Saudi Arabia over the long run. Similar trends have been found in other resource-rich economies, such as Russia, Nigeria, and BRICS countries, where the exploitation of natural resource rent is linked to environmental degradation.

Likewise, economic growth exhibits a statistically significant negative impact on Saudi Arabia's short- and long-term environmental sustainability, as measured by carbon intensity and ecological footprint, at the 5% significance level. These results can be explained by Saudi Arabia's resource-dependent economic model, in which industrial expansion and high consumption of fossil fuels are directly linked to the country's rapid economic growth. In fact, increased economic activity leads to higher energy demand, which in turn raises industrial pollution and CO2 emissions, boosting carbon intensity. Equally, urbanization, infrastructure projects, and manufacturing growth contribute to land degradation and resource depletion, increasing the ecological footprint. Moreover, the error correction term results are statistically significant and negative, proving evidence of a long-term adjustment process. For example, 46.7% of the disequilibrium is corrected in the long run when the carbon intensity is used as a dependent variable.

Assuming all other independent variables remain constant, novel DARDL simulations are designed to automatically produce visual representations that illustrate forecasted changes in the real regressor and how these changes affect the dependent variable. This process forecasts a fluctuation in the influence of geopolitical risk and control of corruption on environmental sustainability measured by carbon intensity and ecological footprint, with an expected increase and decrease of around 10%. Figs. 3 and 4 provide the impact of geopolitical risk on environmental sustainability as described in models 1 and 2. The plots in Fig. 2 demonstrate that a $\pm 10\%$ geopolitical risk shock decreases or increases short-run carbon intensity but not long-run. While geopolitical risk has an insignificant effect on ecological footprint, the plots in Figure 3 might still capture short-term fluctuations or indirect effects. This can be explained by the interactions with other variables, such as economic growth, corruption, or natural resource rents, which influence LFP dynamics. Further, Figs. 5 and 6 exhibit the effects of control corruption shocks on environmental sustainability as outlined in the two models. The plots demonstrate that a $\pm 10\%$ control corruption shock decreases or increases both the short- and long-term.

Table 8. Results of the Novel Dynamic ARDL Approach

	LCI		LFP	
	Coefficient	P-value	Coefficient	P-value
ECT(-1)	-0.467***	0.004	-0.537***	0.001

GPR _{t-1}	0.018	0.541		-0.091	0.639
CC _{t-1}	-0.073***	0.009		-0.390***	0.008
LGDP _{t-1}	0.235**	0.004		0.152**	0.018
LNRT _{t-1}	0.077***	0.006		0.404***	0.007
ΔGPR	0.056*	0.094		0.121	0.549
ΔLGDP	0.232**	0.022		2.253	0.720
ΔLNRT	0.049**	0.013		0.298**	0.033
ΔCC	-0.065*	0.060		-0.496**	0.036
R ²	0.482			0.516	
AdjR ²	0.270			0.318	
RootMSE	0.013			0.026	

*** significance level at 1%, ** significance at 5%, and * significance at 10%

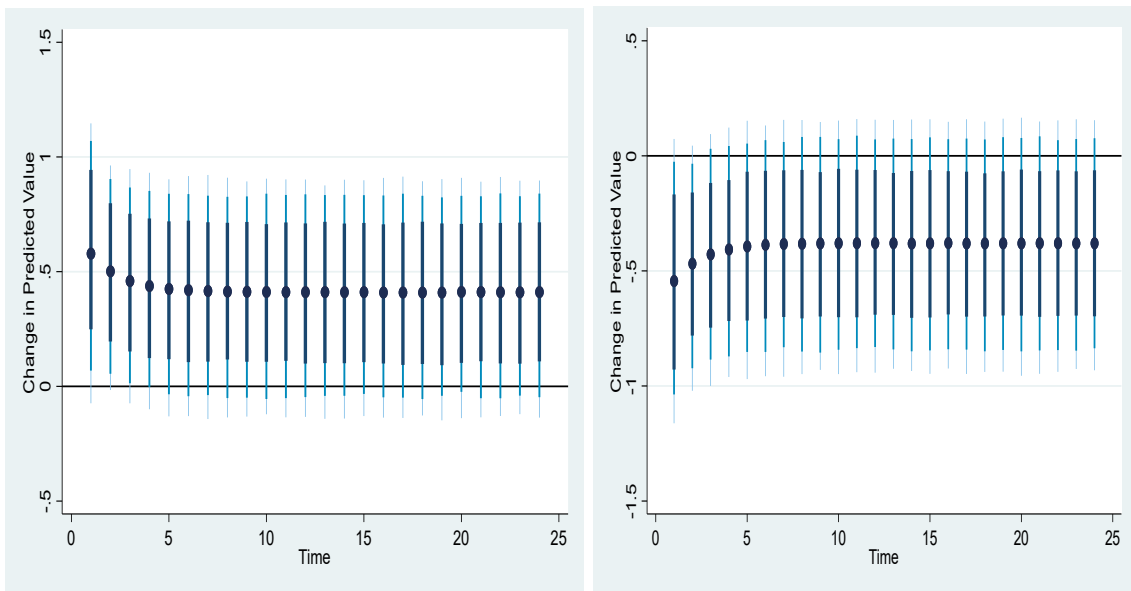


Figure 3. Geopolitical Risk and Carbon Intensity (Model 1)

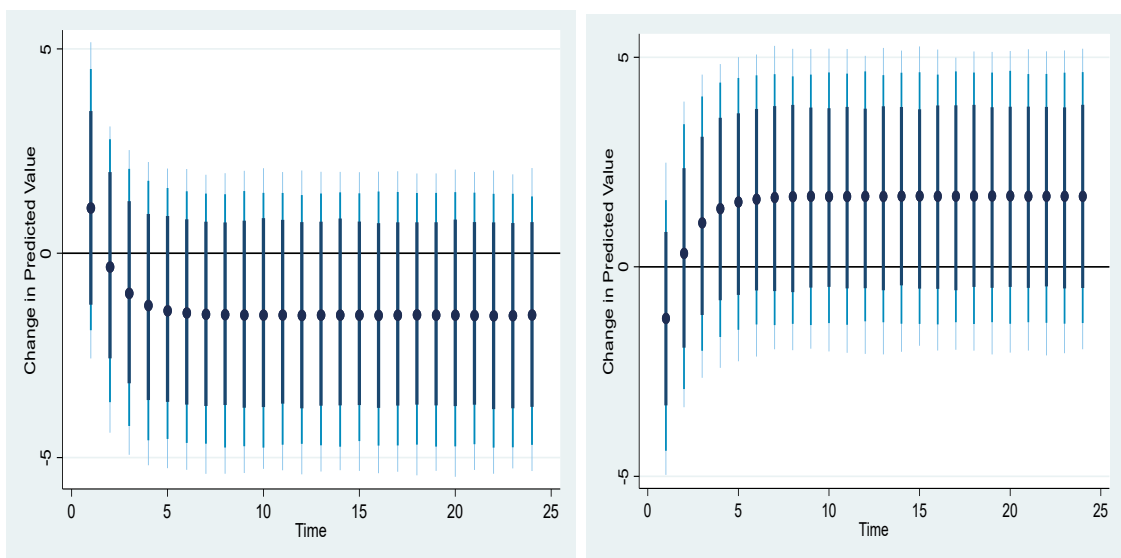


Figure 4. Geopolitical Risk and Ecological Footprint (Model 2)

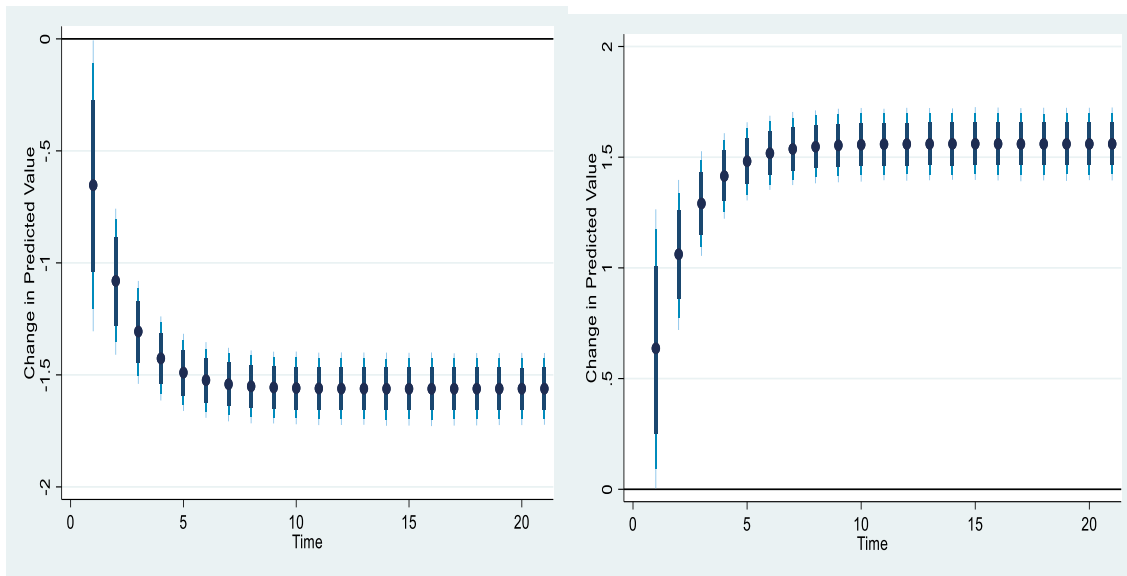


Figure 5. Control of Corruption and Carbon Intensity (Model 1)

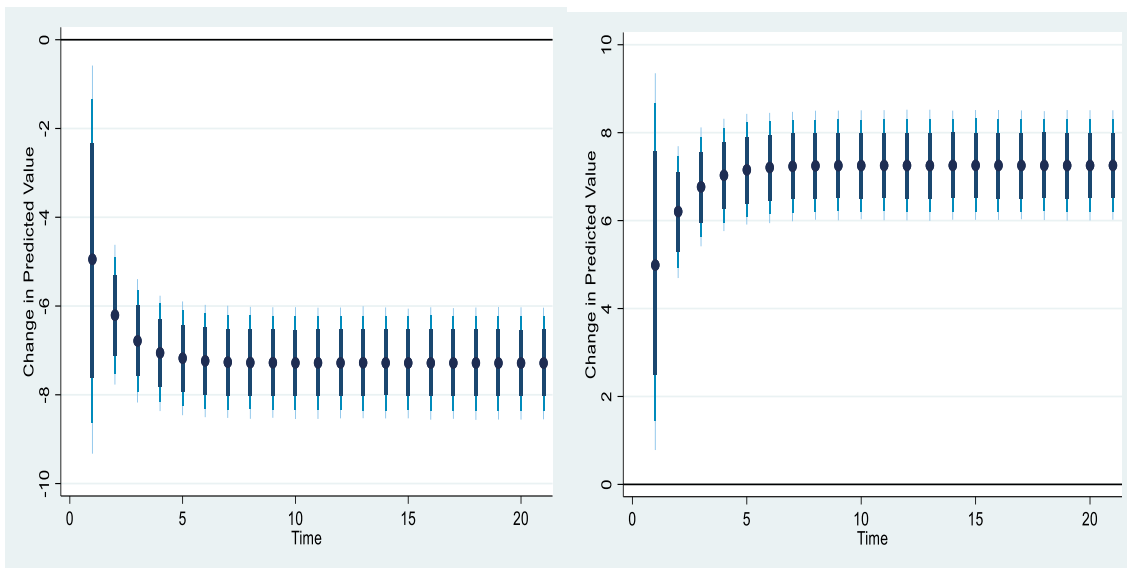


Figure 6. Control of Corruption and Ecological Footprint (Model 2)

Table 9 presents the pointwise derivative results from the KRLS analysis, which highlight the marginal effects of GPR, CC, NRT, and economic growth on carbon intensity and ecological footprint. The average pointwise marginal effect highlighted the importance of geopolitical risk, control of corruption, natural resource rent, and economic growth in the environment for sustainability in Saudi Arabia. All independent variables, except for geopolitical risk, have a statistically significant effect, indicating evidence of a cause-and-effect relationship.

Table 9. Pointwise Derivative (KRLS) Results

	Avg.	SE	t	P> t	P-25	P-50	P-75
Model 1(LCI)							
GPR	-0.001	0.023	-0.027	0.979	-0.030	-0.009	0.032
LNRT	0.068	0.009	7.268	0.000	0.019	0.070	0.111
LGDP	0.101	0.045	2.219	0.035	0.013	0.124	0.190
CC	-0.047	0.009	-5.240	0.000	-0.069	-0.047	-0.026
Diagnostics							
Lambda	0.391	Sigma	4	R2	0.849		
Tolerance	0.032	Eff. df	10.83				
Model 2 (LFP)							
GPR	-0.078	0.155	-0.507	0.616	-0.391	-0.138	0.143
LNRT	0.370	0.059	6.234	0.000	0.033	0.302	0.738
LGDP	0.218	0.333	0.649	0.522	-1.654	-0.038	0.986

CC	-0.330	0.067	-4.885	0.000	-0.567	-0.450	-0.047
Diagnostics							
Lambda	0.057	Sigma	4	R2	0.953		
Tolerance	0.032	Eff. df	17.45				

CONCLUSION AND POLICY RECOMMENDATIONS

Conclusion

Environmental sustainability has emerged as one of the most pressing global challenges of the twenty-first century, driven by the urgent need to address climate change, resource depletion, and ecological deterioration. As one of the world's leading oil producers, Saudi Arabia has an economic structure heavily affected by its dependence on fossil fuels, making the transition to sustainability both imperative and arduous. Saudi Arabia's Vision 2030 underlines the country's commitment to economic diversification, renewable energy development, and environmental protection. Yet, achieving these goals is complicated because geopolitical risks and corruption pose significant barriers to environmental sustainability. This paper investigates the role of GPR and corruption in environmental sustainability. Specifically, it investigates the effect of geopolitical risk, corruption, natural resource rent, and economic growth on environmental sustainability in Saudi Arabia over the period 1990- 2021. To do this, we used the novel Dynamic Autoregressive Distributed Lag (DARDL) model proposed by Jordan and Philips [55] and Kernel-based Regularized Least Squares (KRLS) developed by Hainmueller and Hazlett [59]. The empirical results show that geopolitical risk significantly impacts carbon intensity in the short term. However, its long-term effects remain insignificant, likely due to Saudi Arabia's resilience and adaptability to new geopolitical circumstances in the long run. Conversely, corruption consistently degrades environmental sustainability, elevating carbon emissions and ecological footprint in both the short and long term. Furthermore, NRT and economic growth contribute significantly to environmental degradation, highlighting Saudi Arabia's challenges in transitioning to a sustainable energy future.

Policy Recommendations

Based on these empirical findings, several crucial policy recommendations for Saudi Arabia are proposed. Firstly, the significant impact of geopolitical risk on increasing carbon emissions in the short term underscores the need for Saudi Arabia to implement short-term measures to mitigate the immediate environmental impacts of geopolitical risks. The Saudi government should prioritize energy efficiency measures and temporarily increase investments in renewable energy to offset the reliance on fossil fuels during periods of heightened geopolitical risk. Also, to strengthen its long-term resilience to geopolitical risks, the government should diversify energy sources, reduce reliance on oil exports, and increase investments in renewable energy, as outlined in Vision 2030. These measures will ensure that geopolitical tensions do not derail the country's long-term environmental sustainability goals. Secondly, since corruption undermines environmental sustainability over time, policymakers should take anti-corruption measures. Strengthening the Oversight and Anti-Corruption Authority (Nazaha) and implementing stronger whistleblower protections would improve transparency and accountability in environmental governance. Additionally, this authority should work closely with existing government and regulatory bodies to enforce anti-corruption laws. Thirdly, this study highlights that Saudi Arabia's heavy dependence on natural resource rents worsens environmental degradation. As a result, policymakers must fast-track Vision 2030 initiatives to expand non-oil sectors like technology, tourism, and renewable energy while prioritizing sustainable resource management by implementing stricter environmental regulations on oil and gas extraction and ensuring that production processes comply with international sustainability standards.

Moreover, investing in cleaner extraction technologies and promoting corporate social responsibility in the energy sector can reduce the environmental costs of resource dependency. Lastly, the research shows that Saudi Arabia's current economic growth trajectory contributes to increased carbon intensity and ecological footprint. As a result, the government should promote green industrialization by incorporating energy efficiency and supporting investments in green technologies and carbon capture.

Limitations and future directions

The study reveals certain shortcomings that could lead to further investigation. First, focusing on a single-country context limits the applicability of the results to another country with distinct geopolitical, institutional, and economic circumstances. Saudi Arabia's unique characteristics, such as its heavy reliance on oil exports, centralized governance, and recent economic reforms under Vision 2030, may not be found in other countries. Second, while dynamic ARDL and KRLS approaches offer robust analytical tools to capture both short- and long-term effects, their effectiveness depends on the availability of high-quality time-series data, which may not be readily accessible

in all contexts. Therefore, caution should be exercised when applying this methodological framework to different regions. Future research could extend this approach by incorporating cross-country panel data, which would facilitate comparative analysis and strengthen the external validity of the results. Third, given the evolving nature of global geopolitics and environmental policies, regular updates with current data are necessary to assess the dynamic relationship between geopolitical risk, corruption, and environmental sustainability in Saudi Arabia.

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