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Energy and Sustainable Development Nexus: A Comparative ARDL-based Analysis of Saudi Arabia and Tunisia

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ABSTRACT

This study investigates the dynamics between energy use, trade openness, industrialization, technological innovation, and population density in shaping environmental sustainability in Saudi Arabia and Tunisia. Employing the Autoregressive Distributed Lag (ARDL) model, the research evaluates short- and long-term relationships using data from 1990 to 2022. Key findings reveal that Saudi Arabia's CO2 emissions are predominantly influenced by energy use and trade openness, underscoring the challenges of its fossil-fuel-reliant economy. Conversely, Tunisia demonstrates a faster adjustment to long-term equilibrium, with industrial modernization and trade-related factors reducing emissions. Population density impacts environmental outcomes differently across the two countries, reflecting the influence of urban planning and energy efficiency. These results emphasize the need for tailored sustainability policies, with Saudi Arabia focusing on renewable energy adoption and industrial policy reform, and Tunisia enhancing trade regulations and energy efficiency. This study fills a critical gap in comparative sustainability research in the MENA region by applying a cross-country ARDL model to assess the joint effects of trade, industrialization, technology, energy use, and population dynamics. By contrasting Saudi Arabia's fossil-fuel dependency with Tunisia's diversified economy, it highlights structural asymmetries in environmental outcomes and offers targeted policy insights for resource-diverse nations.

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Keywords: Sustainability; Energy Use; Trade; Industrialization; Population Density; Technology; ARDL; Saudi Arabia; Tunisia; CO2 Emissions

1. INTRODUCTION

The relationship between energy consumption and sustainable development has emerged as a central issue in contemporary economic and environmental policy debates. As nations strive to balance economic growth with environmental preservation and social equity, understanding how energy use impacts key pillars of sustainability becomes essential. By employing the Autoregressive Distributed Lag (ARDL) model, this study conducts a comparative time series analysis to explore the long-run and short-run dynamics between energy use and indicators of sustainable development in Saudi Arabia and Tunisia.

This study focuses on two distinct economies: Saudi Arabia and Tunisia, each presenting unique challenges and opportunities for environmental sustainability. Saudi Arabia, characterized by its resource-dependent economy, relies heavily on fossil fuels and industrial expansion, with its Vision 2030 initiative aiming to diversify the economy and reduce reliance on oil. In contrast, Tunisia, a smaller and more diversified economy, faces sustainability challenges, including energy security and the environmental pressures of trade and industrialization in a developing context. Comparing these nations provides valuable insights into how varying economic structures and policies influence the relationships between technological innovation, energy consumption, trade openness, industrialization, and environmental sustainability.

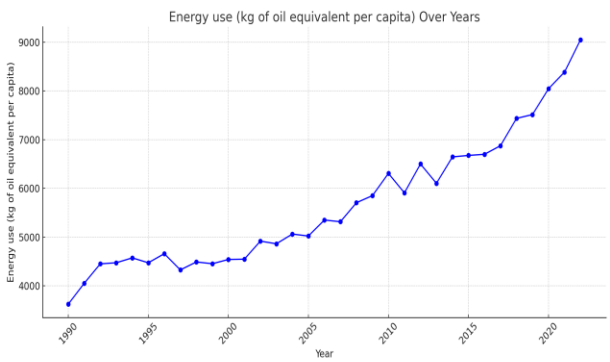

Figure 1. Saudi Arabia Energy Use (1990 – 2022). Source: World Bank https://data.worldbank.org/ (accessed on 29/4/2025)

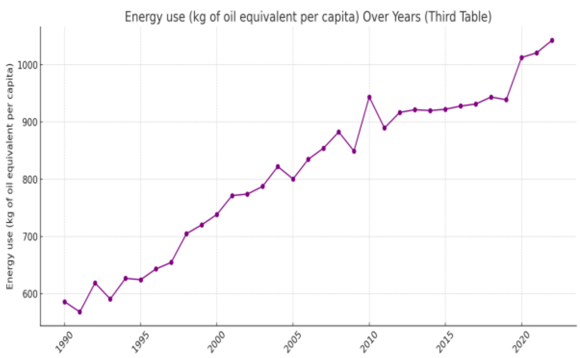

Figure 2. Tunisia Energy Use (1990 – 2022). Source: World Bank https://data.worldbank.org/ (accessed on 29/4/2025)

Technological innovation serves as a double-edged sword in the sustainability discourse. While it can potentially mitigate environmental degradation through cleaner technologies and energy efficiency, it can also drive increased consumption and resource use, particularly in energy-intensive economies like Saudi Arabia. Similarly, energy consumption is a critical factor for both countries. Still, it manifests differently: Saudi Arabia's reliance on fossil fuels contrasts sharply with Tunisia's growing focus on energy diversification and renewable sources.

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Trade openness and industrialization also have profound implications for environmental sustainability. In Saudi Arabia, trade and industrial activities are closely tied to its oil exports and manufacturing sector, which contribute significantly to environmental pressures. Tunisia, as an emerging market with a more diversified trade portfolio, experiences different sustainability impacts, particularly from its export-oriented industries. These differences underscore the importance of context-specific analysis when examining the interplay of these factors.

Despite extensive global research on environmental sustainability, limited comparative studies explore the nuanced dynamics between technology, energy, trade, and industrialization in the contexts of Saudi Arabia and Tunisia. This study addresses this gap by employing the Autoregressive Distributed Lag (ARDL) model to investigate the short- and long-run relationships between these variables and environmental sustainability in both countries. By analyzing and comparing the two nations, this research aims to provide a deeper understanding of the unique and shared challenges they face in their pursuit of sustainable development.

The findings of this study hold significant implications for policymakers in both nations. For Saudi Arabia, they can inform strategies to achieve the goals of Vision 2030 while minimizing environmental harm. For Tunisia, they can guide efforts to balance economic growth with ecological preservation in a resource-scarce context. Additionally, this comparative approach contributes to the broader discourse on sustainability by offering insights into how different economic and policy environments influence the pathways toward environmental sustainability.

This paper is organized as follows: The next section reviews the existing literature, outlining the theoretical and empirical foundations of the study. The methodology section details the ARDL model, data sources, and variables used in the analysis. The results and discussion section presents the empirical findings, comparing and contrasting the two countries. Finally, the paper concludes with key insights and policy recommendations for promoting sustainability in Saudi Arabia and Tunisia.

2. LITERATURE REVIEW

The escalating challenges of climate change, environmental degradation, and resource depletion have placed sustainability at the forefront of global economic and policy discourse. Achieving environmental sustainability, defined as the responsible management of natural resources to meet present needs without compromising future generations, has become imperative, particularly for countries grappling with rapid economic transformation and rising ecological pressures. The interconnected roles of energy consumption, technological advancement, trade liberalization, and industrial development are central to this discourse, as they simultaneously drive economic progress and shape environmental outcomes. Yet, the impacts of these forces are highly context-dependent, varying across nations due to differences in resource endowments, institutional frameworks, development priorities, and policy responses. Therefore, understanding how these variables interact in diverse economic settings is essential for crafting effective, evidence-based strategies for sustainable development.

2.1. The Environmental Kuznets Curve (EKC) and Sustainability

The Environmental Kuznets Curve (EKC) hypothesis remains a foundational framework for understanding the dynamic relationship between economic growth and environmental degradation. It posits an inverted U-shaped relationship wherein environmental deterioration initially rises with economic growth but eventually declines as income increases and cleaner technologies, efficient energy use, and stronger environmental regulations take hold. In this context, energy use plays a pivotal role in determining where a country lies on the EKC trajectory, particularly in economies transitioning from fossil fuels to more sustainable sources.

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Empirical support for the EKC has been established in various settings. For instance, [1] confirmed its validity across OECD countries, demonstrating that renewable energy adoption and financial development contribute to reducing ecological footprints. Similarly, [2] validated the EKC in Saudi Arabia, highlighting the role of urbanization and industrialization in driving CO_2 emissions during early growth stages. However, they noted that long-term income growth, coupled with structural economic reform, could mitigate emissions over time—an outcome still contingent on energy sector reforms.

In developing economies, the EKC pathway is more complex and often hindered by energy constraints. [3] found that in Bangladesh, CO_2 emissions continued to rise with growth unless significant investments in renewable energy and green technologies were made. Saudi Arabia's hydrocarbon-intensive economy, despite its Vision 2030 diversification strategy, remains heavily reliant on fossil fuels, delaying its downward movement along the EKC. Conversely, Tunisia, with a more diversified economy and lower carbon intensity, faces different challenges: limited fiscal and institutional capacity restricts large-scale investments in clean energy, thereby constraining its ability to transition toward sustainability despite moderate income levels.

Although the EKC has not been empirically validated for Tunisia, studies from similar economies suggest that aligning energy use with economic and environmental policy reforms is essential to achieving sustainable development outcomes [4]. This underscores the importance of comparative analysis between countries like Saudi Arabia and Tunisia to understand how energy use trajectories shape their respective sustainability transitions.

2.2. *Energy Use and Sustainability*

The nexus between energy use and sustainability has been extensively analyzed in recent literature, highlighting its pivotal role in shaping environmental and economic outcomes. Research employing the ARDL model has revealed significant insights into the short-term and long-term dynamics between energy consumption and environmental quality. Energy consumption plays a critical role in shaping environmental sustainability and economic growth, with its implications varying across different economic and policy contexts. [5] and [6] highlighted the importance of renewable energy in addressing environmental degradation in South Asia. Their study, using ARDL analysis, demonstrated that renewable energy adoption mitigates the resource curse effect by promoting sustainable economic growth. Similarly, the interaction between energy consumption and trade openness has been a focal point of recent research. while [7] examined Belt and Road Initiative (BRI) countries, revealing the intricate dynamics between energy use, trade, and environmental sustainability. Their findings emphasize the necessity of institutional and policy reforms to harmonize energy use with environmental conservation.

Saudi Arabia's energy mix is still dominated by oil and gas, with high per capita consumption due to subsidized fuel prices and a historically low incentive for efficiency. This contributes to persistently high emissions, with only recent steps toward renewables. Tunisia, conversely, relies more on imported energy and renewables, making energy efficiency a financial imperative. Government initiatives such as the Tunisian Solar Plan signal progress, although scaling remains slow. These differences underline divergent emissions trajectories and policy pressures: Saudi Arabia seeks to green its high-emissions industrial base, while Tunisia prioritizes energy security and affordability in its transition strategy.

In the context of global efforts to align energy use with sustainable development goals (SDGs), renewable energy has emerged as a key focus area. [8] explored China's renewable energy transition under climate and policy uncertainties, underscoring the role of governmental policies in achieving sustainability targets. They argued that a well-structured policy framework could bolster the positive effects of renewable energy adoption on economic performance. In parallel, [9] investigated Pakistan's energy-environment nexus, finding that non-renewable energy sources exacerbate environmental challenges, while green energy solutions significantly improve environmental quality. Their study highlights the need for a comprehensive shift toward green energy strategies, especially in developing countries with high dependency on fossil fuels.

Furthermore, the heterogeneity in natural resource usage and its implications for energy sustainability have garnered attention in recent studies. [10] analyzed the G20 nations, identifying how variations in natural resource endowments influence environmental outcomes. Their findings suggest that green energy and financial mechanisms can play a pivotal role in achieving sustainability, particularly in resource-intensive economies.

2.3. Technological Innovation

Technological innovation (TI) is a transformative factor in achieving environmental sustainability. Studies show that digital and green technologies can significantly reduce emissions by enhancing energy efficiency and promoting cleaner industrial processes. [11] examined Saudi Arabia's efforts to incorporate advanced technologies under Vision 2030 and noted a marked decline in CO_2 emissions attributed to renewable energy technologies and industrial modernization. In the G-7 economies, [12] demonstrated how digital transformation and innovation in financial systems have improved sustainability metrics, particularly when coupled with strong regulatory frameworks. Moreover, innovation is largely state-led and investment-driven, reflected in initiatives like NEOM, smart energy grids, and green hydrogen development under the Vision 2030 umbrella. While these advancements promise emissions reductions, their success hinges on implementation timelines and the private sector's responsiveness. Tunisia, on the other hand, exhibits a more modest innovation ecosystem. Its innovation outputs are often linked to foreign partnerships, small-scale renewable projects, or donor-driven development initiatives, limiting their transformative impact on national emissions. Consequently, while TI is present in both countries, its influence is moderated by institutional, financial, and absorptive capacities.

In Bangladesh, however, [3] highlighted the limited impact of TI due to infrastructural and financial constraints. This suggests that the benefits of technological advancements depend heavily on the enabling environment, including policy support and investment in research and development [13].

Globally, the integration of renewable energy technologies and artificial intelligence (AI) in energy systems has been found to optimize resource use and reduce emissions significantly [14]; [15]. For Tunisia, expanding innovation in renewable technologies could address existing gaps in energy efficiency and industrial emissions [16].

2.3.

2.4. Trade Openness

Trade openness (TO) influences environmental sustainability through multiple pathways, including technology transfer, industrial expansion, and resource utilization. While trade facilitates access to cleaner technologies, it can also exacerbate resource depletion and emissions. [17] found in Turkiye that TO improved environmental sustainability in the short run but negatively impacted it over the long term due to increased industrial activities.

For Saudi Arabia, [2] emphasized that trade-driven industrialization significantly increases CO_2 emissions, underscoring the need for stringent environmental regulations. Similarly, [18] highlighted the mixed outcomes of TO, stressing the importance of aligning trade policies with sustainable development goals.

In Saudi Arabia, exports are heavily concentrated in oil and petrochemicals, linking trade to emissions via extraction and refining. Thus, increased trade volumes often exacerbate environmental pressures. Tunisia's trade structure is more balanced, with substantial shares in agriculture, textiles, and mechanical equipment, which are less carbon-intensive but still tied to industrial emissions. Trade liberalization has introduced cleaner technologies but also increased production pressures. The environmental effects of trade thus differ structurally between the two economies—Saudi trade amplifies fossil-fuel-driven emissions, while Tunisia faces a subtler trade–environment trade-off mediated by sectoral composition.

5. Industrialization

Industrialization is a major driver of economic growth, but also a significant contributor to environmental degradation. [2] demonstrated that Saudi Arabia's reliance on oil-based industrialization has led to rising CO_2 emissions, requiring robust environmental policies to mitigate the impact. [19] analyzed industrialization across developing nations, emphasizing the need for organizational, technological, and political reforms to balance growth with environmental sustainability.

In Tunisia, industrial growth has supported economic diversification but has also intensified environmental challenges. Comparative insights from countries like Bangladesh suggest that industrial upgrading through cleaner technologies can align industrialization with sustainability goals [3]; [15].

Comparative studies reveal divergent pathways to sustainability for Saudi Arabia and Tunisia. Saudi Arabia, with its financial capacity and Vision 2030 initiatives, has leveraged investments in renewable energy and advanced technologies to address environmental challenges. Tunisia, with fewer resources, must prioritize regional cooperation and targeted policies to adopt sustainable practices. Lessons from Turkiye emphasize the importance of robust policy frameworks to balance trade, industrialization, and sustainability.

2.6. Population Density and Sustainability

Population density significantly influences environmental and economic sustainability, particularly in rapidly urbanizing regions [20] explored the relationship between population density and environmental pollutants in Benin, utilizing ARDL and Auto-regressive Integrated Moving Average (ARIMA) models. Their findings reveal that higher rural population densities exacerbate environmental challenges, particularly through increased emissions from agricultural activities and urban expansion. Similarly, [21] examined how socio-demographic factors like population density affect green finance growth, finding that densely populated areas demand robust environmental financing mechanisms to balance economic growth with sustainability.

In the context of climate policy, [22] highlighted the asymmetric impacts of population density on housing markets and sustainability outcomes. Using panel quantile ARDL, the study shows that higher population densities in urban areas amplify heating stress, requiring targeted interventions for equitable and sustainable housing solutions. [23] Provided further evidence of the mixed effects of urban population density, noting that dense urban areas often experience environmental degradation but also benefit from economies of scale in infrastructure and energy use, thus requiring nuanced policy frameworks to achieve sustainability.

Globally, population density has been linked to ecological footprint dynamics. [24] Compared Finland and Japan, showing that higher population densities combined with industrial growth increase ecological stress, necessitating innovative urban planning and resource management strategies.

2.7. ARDL-Based Studies and Distinctiveness of This Research

Several recent studies have employed dynamic econometric models, particularly the Autoregressive Distributed Lag (ARDL) framework, to examine the interplay between environmental sustainability indicators and macroeconomic variables. For instance, [25] analyzed the dynamic relationships between energy use, technological innovation, trade openness, and economic growth in Malaysia using the ARDL approach, concluding that trade and energy consumption significantly influenced long-term

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environmental outcomes. Similarly,[26] tested the Environmental Kuznets Curve (EKC) hypothesis for Tü-rkiye using the ARDL bounds testing approach, finding that renewable energy and economic complexity helped mitigate environmental degradation. In the context of South Africa, [27] used the ARDL model to examine the causal link between economic growth, CO_2 emissions, and energy consumption, confirming a feedback relationship between emissions and energy use. [28] adopted a dynamic ARDL model to evaluate the effects of ICT and renewable energy on environmental sustainability in China, revealing that green technology adoption significantly reduces CO_2 emissions in the long run. Closer to this study's context, [29] utilized an ARDL model to assess the impact of renewable energy and industrial expansion on Saudi Arabia's environmental footprint, providing country-specific insights but without a comparative regional framework. Unlike these studies, the present research adopts a comparative cross-country ARDL approach covering both Saudi Arabia and Tunisia, incorporates a broader set of structural and demographic variables (e.g., population density, industrialization, trade openness, and technological in-novation), and complements the ARDL analysis with robustness checks using DOLS, ECM, Johansen cointegration, and Granger causality. This integrated design offers a more holistic understanding of how structural economic features influence sustainability dynamics in resource-diverse economies.

Despite an expanding body of literature on environmental sustainability, critical gaps remain, particularly in the contexts of Saudi Arabia and Tunisia. Most existing studies focus on single-country analyses and fail to consider how differing economic structures shape environmental outcomes. While renewable energy and technological innovation are widely acknowledged as pivotal for sustainability, limited attention is paid to the institutional, financial, and governance barriers faced by emerging economies in implementing these strategies effectively. Likewise, the long-term effects of trade openness and its interaction with industrialization in resource-rich versus developing economies remain unclear. Furthermore, the dual role of industrialization as both a driver of growth and a source of environmental pressure is often overlooked, especially in nations transitioning from fossil fuel dependency. Additionally, insufficient emphasis has been placed on regional sustainability dimensions, including cross-border resource management and long-term policy effects, through dynamic econometric modeling. This study fills these gaps by offering a comparative, multi-variable analysis using ARDL techniques to uncover the short- and long-term drivers of environmental sustainability in two structurally contrasting economies: Saudi Arabia and Tunisia.

3. METHODOLOGY

3.1. Data Description

This study utilizes annual data from 1990 to 2022 for Saudi Arabia and Tunisia, collected from reputable international and national databases, including the World Bank's World Development Indicators (WDI), the International Energy Agency (IEA), and respective national statistical agencies. The key variables include:

- CO_2 Emissions (Metric Tons per Capita): Proxy for environmental sustainability and the dependent variable denoted by (CO_2). The following are acting independent variables:

- Gross Domestic Product (Constant US$): A measure of economic growth and development, denoted by GDP.

- Trade Openness (Index): Calculated as the ratio of the sum of exports and imports to GDP, denoted by (TO).

- Energy use (kWh per Capita): A measure of energy use, with a focus on renewable versus non-renewable sources, denoted by (EnU).

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- Technological Innovation (Index or Patent Count): A proxy for technological advancements, denoted by (TI).

- Industry value added (Manufacturing Value Added as % of GDP): Represents industrial activity, denoted by (IVA).

- Population density (people per sq. km of land area): represents the intensity of human habitation over land, denoted by (PoD).

The variables selected are grounded in established economic and environmental theories: technological innovation reflects the environmental modernization hypothesis; industrialization aligns with the EKC framework; energy use captures the dual role of growth and emissions; trade openness accounts for scale and technique effects; and population density reflects demographic and urbanization pressures. Together, they offer a comprehensive view of sustainability drivers. Although the sample includes only 33 annual observations per country, the ARDL model is well-suited to small samples, and the data—sourced from national and international databases, ensures accuracy and representativeness for both Saudi Arabia and Tunisia.

3.2. ARDL Model Justification

The ARDL model is employed for its flexibility in handling variables integrated at I(0) and I(1), its ability to estimate both short- and long-run dynamics, and its suitability for small sample sizes. The ARDL bounds testing approach was used to identify long-run relationships, with stationarity confirmed via Phillips-Perron unit root tests. Lag selection was guided by AIC and SC criteria. Model robustness was validated through Johansen cointegration, Granger causality, and the estimation of an error correction term (ECT) to capture short-run adjustments. To address potential heteroscedasticity, the study applied robust standard errors and performed diagnostic tests for autocorrelation and residual normality. Assumptions of linearity, normality, and homoscedasticity were observed. Additional robustness checks using DOLS supported the reliability of long-run estimates.

Furthermore, given that Johansen cointegration tests confirmed the presence of long-run relationships among the variables, the study employed a Vector Error Correction Model (VECM) for system-wide dynamic modeling. Unlike the standard VAR, the VECM is theoretically appropriate in the presence of cointegration, as it incorporates the error correction mechanism and preserves the long-term equilibrium structure of the data.

3.3. Model Specification

The study employs the ARDL model to investigate the short- and long-run relationships between CO_2 emissions and their determinants, including GDP, trade openness, energy consumption, technological innovation, and industrialization. The ARDL approach, introduced by [30], is well-suited for this analysis because it accommodates mixed levels of integration among variables, whether integrated of order I(0) or I(1)—without requiring all variables to be of the same order. This flexibility is particularly advantageous in studies of environmental sustainability, where variables such as energy use and trade openness often exhibit mixed stationarity [31]. Additionally, the ARDL model allows for simultaneous estimation of short- and long-run dynamics, making it ideal for assessing both immediate and sustained impacts of economic activities on environmental outcomes, as shown in studies like [17] on Turkiye and [2] on Saudi Arabia. The long-run relationships between variables are tested using the ARDL bounds testing procedure, which is effective for small sample sizes, a common challenge in environmental studies covering limited time frames [3]. The robustness of this approach has been validated in numerous studies, including those by [32] on the environmental effects of urbanization and by [4], who explored the role of renewable energy and trade openness in ecological sustainability. Thus, the ARDL model provides a comprehensive econometric framework to analyze how economic and technological factors

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interact to shape CO_2 emissions in Saudi Arabia and Tunisia. The general formula of this relation can be expressed as:

$$SCO_{2\,it} = F(GDP_{it}, TO_{it}, EnU_{it}, TI_{it}, IVA_{it}, PoD_{it}) \quad (1)$$

$$TCO_{2\,it} = F(GDP_{it}, TO_{it}, EnU_{it}, TI_{it}, IVA_{it}, PoD_{it}) \quad (2)$$

Where:

- SCO_{2it} is the Carbon dioxide emission in Saudi Arabia.
- TCO_{2it} is the Carbon dioxide emission in Tunisia.
- GDP_{it} is the Gross Domestic Product for both countries.
- TO_{it} is the Trade Openness for both countries.
- EnU_{it} is the Energy use for both countries.
- TI_{it} is Technological Innovation for both countries.
- IVA_{it} is Industry Value Added for both countries.
- PoD_{it} is the population density for both countries.

After taking the first differentiation, equations (1) and (2) become:

$$Ln\ CO2_{it} = \alpha_0 + \alpha_1 Ln\ GDP_{it} + \alpha_2 Ln\ TO_{it} + \alpha_3\ Ln\ EnU_{it} + \alpha_4\ Ln\ TI_{it} + \alpha_5\ Ln\ IVA_{it} + LnPoD_{it}\ \varepsilon_{it} \quad (3)$$

ARDL Model

The general ARDL model for this study is specified as:

$$\Delta Yt = \alpha 0 + \sum_{i=1}^{p} \beta i \Delta Yt - i + \sum_{j=1}^{q} \beta i \Delta Yt - j + \gamma j \Delta Xt - j + \phi 1 Yt - 1 + \phi 2 Xt - 1 + \epsilon t \quad (4)$$

Where:

- Y_t : Dependent variable (CO_2 emissions).
- X_t : Vector of independent variables (GDP, trade openness, energy Use, technological innovation, industry value added, and population density).
- Δ: First-difference operator.
- α_0: Constant term.
- β_i, γ_j: Short-run coefficients.
- ϕ_1, ϕ_2: Long-run coefficients.
- ϵ_t: Error term.
- $_t$: Time period.

For bounds testing, the null hypothesis of no cointegration (H0: $\phi 1 = \phi 2 = 0$H_0) is tested against the alternative hypothesis of cointegration (H1: $\phi 1 \neq 0$ or $\phi 2 \neq 0$).

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The analysis investigates the relationships between the variables in both the short and long run. After confirming cointegration, the long-run coefficients are estimated using Equation (3), and the error correction term (ECT) is calculated to assess short-term dynamics and the speed of adjustment toward long-run equilibrium, as presented in Equation (4).

$$\Delta Y_t = \alpha_0 + \sum_{i=1}^{p} \beta i \Delta Y_{t-i} + \sum_{j=0}^{q} \gamma j \Delta Y_{t\text{-}j} + \lambda ECT_{t-1} + \epsilon_t$$

Where:

- ΔYt: Change in the dependent variable (CO_2 emissions).
- $\Delta Xt-j$: Change in the independent variables (GDP, trade openness, energy use, technological innovation, industry value added, and population density).
- α_0: Constant term.
- $\beta i, \gamma j$: Short-run coefficients of the lagged differences of the variables.
- ECT_{t-1}: Error correction term, derived from the long-run cointegration equation.
- λ: Speed of adjustment coefficient, which measures how quickly the system returns to equilibrium after a short-run shock. It is expected to be negative and statistically significant.
- ϵ_t: White noise error term.

3.4. Diagnostic and Supporting Tests

To ensure robustness and validity, the following econometric diagnostics were conducted:

- Unit Root Tests (Phillips-Perron): To assess stationarity and determine the order of integration.
- VAR Lag Selection and Johansen Cointegration Tests: To confirm the number of cointegrating vectors and validate the ARDL findings in a multivariate context.
- ARDL Bounds Testing: To establish the existence of long-run cointegration among the variables.
- Error Correction Model (ECM): To evaluate short-term dynamics and the speed of adjustment.
- Dynamic OLS (DOLS): To complement ARDL estimations and enhance inference accuracy.
- Granger Causality Tests: To explore directional relationships and causal linkages.

Furthermore, the study used the Breusch-Godfrey serial correlation test to check model adequacy.

4. RESULTS OF THE ANALYSES

4.1. Descriptive Statistics

The descriptive statistics for Saudi Arabia and Tunisia reveal notable differences and similarities in their economic and environmental variables. As shown in Table 1, Saudi Arabia exhibits higher mean values across all variables, such as CO_2 emissions ($LnCO_2$: 2.5738 vs. 0.8096), energy use (LnEnU: 8.6067 vs. 6.6839), and technology innovation (LnTI: 7.0109 vs. 5.7463), reflecting its larger scale of activities. Variability is generally higher in Saudi Arabia, especially for investment (LnTI), while Tunisia shows more stability in industry value added output (LnIVA) and population density (LnPoD). Both countries display symmetrical distributions, with slight negative skewness for most variables and positive skewness for trade openness (LnTO) in Tunisia. Kurtosis values below 3 in both datasets suggest flatter distributions, and the Jarque-Bera test confirms approximate normality for all variables, ensuring suitability for econometric modeling. These findings highlight Saudi Arabia's larger economic scale and

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Tunisia's comparative stability, setting the stage for a meaningful comparative analysis of sustainability determinants.

Table 1. Descriptive statistics

Country	Statistic	Mean	Median	MAX	MIN	Std. Dev.	Jarq-Bera	Prob	Sum
KSA	$LnCO_2$	2.57	2.55	2.85	2.37	0.15	2.70	0.26	77.21
Tunisia		0.81	0.85	1.01	0.55	0.14	3.02	0.22	26.72
KSA	LnEnU	8.61	8.53	9.11	8.20	0.24	2.06	0.36	258.20
Tunisia		6.68	6.73	6.95	6.34	0.18	2.67	0.26	220.57
KSA	LnTI	7.01	6.75	8.35	6.12	0.74	3.73	0.16	210.33
Tunisia		5.75	6.07	6.52	4.63	0.60	3.45	0.18	189.63
KSA	LnTId	3.93	3.92	4.15	3.68	0.13	0.82	0.66	117.85
Tunisia		3.29	3.29	3.45	3.07	0.09	1.34	0.51	108.57
KSA	LnPoD	2.45	2.41	2.82	2.01	0.27	2.45	0.29	73.64
Tunisia		4.21	4.21	4.37	3.99	0.11	1.55	0.46	138.87
KSA	LnTO	4.23	4.21	4.55	3.91	0.15	0.57	0.75	126.84
Tunisia		4.52	4.53	4.76	4.36	0.11	1.40	0.50	149.28

The correlation analysis reveals notable numerical differences between Saudi Arabia and Tunisia in the relationships among CO2 emissions, energy, investment, industrial output, population, and trade openness. Table 2 indicates that in Saudi Arabia, CO2 emissions are strongly correlated with energy use (LnEnU: 0.8272) and population density (LnPoD: 0.9024), whereas the correlation with trade openness (LnTO: 0.1302) is weak. Industry value added output has a negligible correlation with emissions (LnIVA: 0.0578) and energy use (LnEnU: -0.1433) but a strong positive correlation with LnTO (0.8917). Technology innovation in Saudi Arabia shows moderate correlations with emissions (LnTI: 0.5852) and LnEnU (0.8249) but a strong negative correlation with LnIVA (-0.5649). In Tunisia, CO2 emissions are more strongly correlated with LnEnU (0.9628) and LnPoD (0.9414) compared to Saudi Arabia, with a moderate correlation with LnTO (0.5312). Industry value added has a weak negative correlation with emissions (-0.3684) and energy use (-0.4643) but a weaker connection with lnTO (0.2239) than in Saudi Arabia. Tunisia's trade openness exhibits moderate correlations with energy (0.5115), technology innovation (0.5589), and emissions (0.5312), reflecting its greater integration with economic and environmental variables. These numerical insights emphasize the structural differences in the sustainability dynamics of the two nations, with Saudi Arabia's economy more reliant on energy and population, while Tunisia exhibits stronger trade integration.

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Table 2. Saudi's correlation matrix

	LN CO_2	LNENU	LNTI	LNTID	LNPOP	LNTO
$LnCO_2$	1					
LnEnU	0.83	1.00				
LnTI	0.59	0.82	1.00			
LnIVD	0.06	-0.14	-0.56	1.00		
LnPoD	0.90	0.96	0.76	-0.04	1.00	
LnTO	0.13	-0.21	-0.60	0.89	-0.11	1

Table 3. Tunisia correlation matrix

	LN CO_2	LNENU	LNTI	LNTID	LNPOP	LNTO
$LnCO_2$	1.00					
LnEnU	0.96	1.00				
LnTI	0.88	0.85	1.00			
LnIVD	-0.37	-0.46	-0.17	1.00		
LnPoD	0.94	0.98	0.83	-0.57	1.00	
LnTO	0.53	0.51	0.56	0.22	0.47	1.00

4.2. Dynamic Ordinary Least Squares (DOLS)

The DOLS regression results highlight distinct drivers of CO2 emissions in Saudi Arabia and Tunisia. Based on Table 4, in Saudi Arabia, population density (LnPoD: 1.0099, p = 0.0057) and trade openness (LnTO: 0.6815, p = 0.0222) are significant contributors to emissions, while investment (LnTI: -0.1331, p = 0.0093) significantly reduces emissions, reflecting its potential for fostering cleaner technologies. Energy use (LnEnU: -0.1227, p = 0.0828) and industrial output (LnIVA: -0.2218, p = 0.1269) show weaker and statistically insignificant effects. Conversely, in Tunisia, energy consumption (LnEnU: 0.9574, p = 0.0027) and investment (LnTI: 0.1066, p = 0.0022) significantly increase emissions, while population growth (LnPoD: -1.2593, p = 0.0146) has a mitigating effect, likely due to energy efficiency or lower per-capita emissions. Trade openness (LnTO: 0.0625, p = 0.6517) and industrial output (LnIVA: -0.2422, p = 0.0978) are insignificant in Tunisia. These findings suggest Saudi Arabia's emissions are population- and trade-driven, while Tunisia's are energy- and investment-driven, emphasizing the need for tailored sustainability policies in each country.

Table 4. DOLS estimation results

Country	Variable	Coefficient	Std. Error	t-Stat	Prob.
Saudi Arabia	LnEnU	-0.123	0.016	-7.644	0.083
Tunisia		0.957	0.234	4.091	0.003

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Saudi Arabia	LnTI	-0.133	0.002	-65.129	0.009
Tunisia		0.107	0.025	4.242	0.002
Saudi Arabia	LnIVA	-0.222	0.045	-4.949	0.127
Tunisia		-0.242	0.131	-1.847	0.098
Saudi Arabia	LnPoD	1.010	0.009	110.744	0.006
Tunisia		-1.259	0.418	-3.014	0.015
Saudi Arabia	LnTO	0.682	0.024	28.959	0.022
Tunisia		0.062	0.133	0.469	0.652
Saudi Arabia	C	-0.065	0.182	-0.359	0.729
Tunisia		-0.261	1.034	-0.252	0.807

4.3. Unit Root Test

Table 5 provides results of unit root tests for variables at their levels, first differences, and second differences (where applicable) for Saudi Arabia and Tunisia. The null hypothesis for the unit root tests is that the variable has a unit root (non-stationary). The t-statistics are compared to critical values at the 1%, 5%, and 10% levels, and the probability values (p-values) determine whether the null hypothesis can be rejected.

The results in Table 5 indicate that most variables for both Saudi Arabia and Tunisia are non-stationary at their levels but become stationary at their first differences, signifying they are integrated of order 1 ($I(1)$). For Saudi Arabia, $LnCO_2$, LnEnU, LnTI, LnIVA, LnPoD, and LnTO are non-stationary at levels ($t > -2.62$, $p > 0.05$) but stationary at first differences ($t < -3.65$, $p = 0.00$), except for LnPoD, which requires second differencing to achieve stationarity ($t = -3.25$, $p = 0.03$). In Tunisia, all variables except LnPoD at level ($t = -3.83$, $p = 0.01$) are also non-stationary at levels and become stationary at first differences, as seen with CO_2 emissions ($t = -7.62$, $p = 0.00$), LnEnU ($t = -10.97$, $p = 0.00$), technology innovation ($t = -3.52$, $p = 0.01$), LnIVA ($t = -4.98$, $p = 0.00$), and LnTO ($t = -11.07$, $p = 0.00$). These results highlight that most variables are I(1), with Tunisia's LnPoD stationary at level and Saudi Arabia's LnPoD requiring second differencing I(2). These findings underline the importance of appropriate differencing for stationarity before conducting econometric analyses such as ARDL or cointegration modeling.

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Table 5. Phillips-Perron unit root test results

Country	Variable	Level critical values					First Difference critical values					Second difference critical values				
		1 %	**5 %**	**10 %**	**t-stat**	**Prob.**	**1 %**	**5 %**	**10 %**	**t-stat**	**Prob.**	**1 %**	**5 %**	**10 %**	**t-stat**	**Prob.**
Saudi Arabia	LNCO2	-3.65	-2.95	-2.62	-1.40	0.57	-3.65	-2.96	-2.62	4.03	0.00					
Tunisia		-3.65	-2.96	-2.62	-1.74	0.40	-3.66	-2.96	-2.62	-7.62	0.00					
Saudi Arabia	LnEnU	-3.65	-2.96	-2.62	0.20	0.97	-3.66	-2.96	-2.62	-8.55	0.00					
Tunisia		-3.65	-2.96	-2.62	-1.02	0.74	-3.66	-2.96	-2.62	-10.97	0.00					
Saudi Arabia	LnTI	-3.69	-2.97	-2.63	-0.52	0.87	-3.72	-2.99	-2.63	-3.96	0.01					
Tunisia		-3.65	-2.96	-2.62	-1.25	0.64	-3.66	-2.96	-2.62	-3.52	0.01					
Saudi Arabia	LnIVA	-3.65	-2.95	-2.62	-2.04	0.27	-3.65	-2.96	-2.62	-6.17	0.00					
Tunisia		-3.65	-2.95	-2.62	-1.51	0.52	-3.65	-2.96	-2.62	-4.98	0.00					

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Saudi Arabia	LnPoD	-3.65	-2.95	-2.62	-2.69	0.09	-3.65	-2.96	-2.62	-0.50	0.88	-3.7	-2.96	-2.62	-3.25	0.03
Tunisia		-3.65	-2.96	-2.62	-3.83	0.01										
Saudi Arabia	LnTO	-3.65	-2.95	-2.62	-1.47	0.54	-3.65	-2.96	-2.62	4.76	0.00					
Tunisia		-3.65	-2.95	-2.62	-2.30	0.18	-3.65	-2.96	-2.62	-11.07	0					

4.4. Model Adequacy Checking

Breusch-Godfrey Serial Correlation LM Test

The Breusch-Godfrey Serial Correlation LM test is a diagnostic tool used to detect the presence of autocorrelation in the residuals of a regression model, particularly when higher-order lags are involved. Based on Table 6, the residual diagnostics for both Saudi Arabia and Tunisia confirm the validity of the ARDL model and the absence of serial correlation, ensuring reliable inference. For Saudi Arabia, the Breusch-Godfrey Serial Correlation LM test shows no evidence of autocorrelation up to two lags, with p-values of 0.4036 (F-statistic) and 0.2304 (Chi-square), both exceeding the 0.05 threshold. This is further supported by a Durbin-Watson statistic of 1.75, indicating near-ideal independence of residuals. The lagged residual terms, including RESID(-1) and RESID(-2), are statistically insignificant, and the model's low R-squared (0.10) and insignificant F-statistic (p = 0.9973) are consistent with a well-specified residual regression. For Tunisia, similar findings emerge. The LM test again confirms no significant autocorrelation, with an F-statistic of 1.1195 (p = 0.3540) and Chi-square statistic of 4.2744 (p = 0.1180). The Durbin-Watson statistic of 2.069 reinforces this conclusion. Both RESID(-1) and RESID(-2) are statistically insignificant (p = 0.8931 and 0.1574, respectively), and the residual model's R-squared (0.1379) and F-statistic (p = 0.9998) again indicate a lack of systemic patterns in residuals—an expected outcome in a correctly specified model. Collectively, these diagnostics demonstrate that the ARDL models for both countries are free from serial correlation and misspecification, supporting the robustness of the estimated relationships and ensuring the validity of policy inferences derived from the analysis.

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Table 6. Breusch-Godfrey serial correlation LM results

Statistic	Country's Model	Value	Prob.
F-statistic	Saudi Arabia	0.958	0.4036 (F (2,17))
	Tunisia	1.11955	0.354 (F (2,14))
Obs*R-squared	Saudi Arabia	2.936	0.2304 (Chi-Square (2))
	Tunisia	4.274	0.118 (Chi-Square (2))
Durbin-Watson	Saudi Arabia	1.748	
	Tunisia	2.069	
RESID(-1)	Saudi Arabia		**0.232**
	Tunisia		0.659
RESID(-2)	Saudi Arabia		**0.893**
	Tunisia		0.157

4.5. Cointegration Test Results

4.5.1. Johansen Test

The Johansen cointegration test identifies the presence and number of long-term equilibrium relationships among variables in a multivariate time series model based on trace and eigenvalue statistics. Table 7 presents the results of the Trace test for cointegration in Saudi Arabia and Tunisia. The Trace test examines the null hypothesis of no cointegration (or a limited number of cointegrating equations) among the variables. The results are compared against the critical values at the 5% significance level, and the p-values indicate whether the null hypothesis can be rejected. The Trace test results indicate the presence of 4 cointegrating equations in Saudi Arabia and 6 cointegrating equations in Tunisia at the 5% significance level. These findings suggest long-term equilibrium relationships among the variables in both countries. Tunisia exhibits a stronger presence of cointegration compared to Saudi Arabia, as indicated by the number of cointegrating equations. This implies a higher degree of interconnectedness among the variables in the Tunisian dataset.

Table 7. Johansen cointegration test results

Country	Hypothesized No. of CE(s)	Eigen-value	Trace Statistic	0.05 Critical Value	Prob.
Saudi Arabia	None *	0.92	185.15	95.75	0.00
Tunisia		0.85	173.18	95.75	0.00
Saudi Arabia	At most 1 *	0.91	123.09	69.82	0.00

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Tunisia		0.79	114.51	69.82	0.00
Saudi Arabia	At most 2 *	0.75	64.17	47.86	0.00
Tunisia		0.66	66.71	47.86	0.00
Saudi Arabia	At most 3 *	0.60	31.36	29.80	0.03
Tunisia		0.35	33.61	29.80	0.02
Saudi Arabia	At most 4	0.23	9.37	15.49	0.33
Tunisia		0.32	20.20	15.49	0.01
Saudi Arabia	At most 5	0.13	3.21	3.84	0.07
Tunisia		0.24	8.37	3.84	0.00

* Rejection of the hypothesis at the 0.05 level; ** MacKinnon-Haug-Michelis [33]. p-values.

4.5.2. The Vector Error Correction Model

The Vector Error Correction Model (VECM) is an econometric framework used to capture both short-run dynamics and long-run equilibrium relationships among cointegrated time series variables. The VECM results in Table 8 for Tunisia and Saudi Arabia highlight both shared and distinct dynamics in the drivers of CO_2 emissions. In both countries, trade openness emerges as a significant or near-significant short-run contributor to emissions, underlining its critical role in environmental degradation. For Tunisia, energy consumption is also a significant short-run driver, while in Saudi Arabia, industry value added shows a marginally significant negative effect, suggesting that cleaner or more efficient industrial practices may help curb emissions. In contrast, energy use, population density, and technology innovation do not show significant short-term effects in Saudi Arabia. The error correction term is highly significant and negative in both cases, indicating a long-run equilibrium relationship: Tunisia corrects 58% of disequilibrium annually, reflecting strong convergence, while Saudi Arabia adjusts more gradually at 31% per year. These findings reinforce the importance of context-specific energy, trade, and industrial policies in addressing environmental sustainability and underscore the structural differences in how each country responds to economic and environmental shifts.

Table 8. Vector error correction model results (short-run)

Variable	**Country**	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
D(LnEnU)	Saudi Arabia	0.1661	0.1387	1.1973	0.2452
	Tunisia	0.2921	0.1289	2.2667	0.0320
D(LnTI)	Saudi Arabia	-0.0002	0.0244	-0.0076	0.9940
	Tunisia	-0.0028	0.0234	-0.1200	0.9054
D(LnIVA)	Saudi Arabia	-0.2565	0.1263	-2.0312	0.0557

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	Tunisia	-0.2453	0.1667	-1.4717	0.1531
D(LnPoD)	Saudi Arabia	0.1275	0.2438	0.5232	0.6066
	Tunisia	0.5494	0.4323	1.2710	0.2150
D(LnTO)	Saudi Arabia	0.2496	0.1290	1.9348	0.0673
	Tunisia	0.2130	0.0923	2.3079	0.0292
ECM(-1)	Saudi Arabia	-0.3140	0.1440	-2.1807	0.0413
	Tunisia	-0.5776	0.1484	-3.8927	0.0006

4.5.2. Error Correction Model

The ARDL results in Table 9 reveal that in Saudi Arabia, energy consumption, technology innovation, and trade openness positively impact CO_2 emissions in the short term, while industry value added and population show no consistent effects. The error correction term (−0.42, p = 0.00) indicates a 42% adjustment toward equilibrium per period. In Tunisia, energy use and technology innovation exhibit lagged negative effects on emissions, while trade openness consistently increases emissions in the short term. Industry value added significantly reduces emissions (−0.46, p = 0.00), highlighting structural shifts in industry. Tunisia's error correction term (−1.11, p = 0.00) suggests a faster 111% adjustment toward long-term equilibrium compared to Saudi Arabia. This reflects stronger convergence dynamics and varying short-term emission drivers between the two countries

Table 9. ECM regression results (long-run)

Country	**Variable**	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
Saudi Arabia	D(LnEnU)	0.29	0.08	3.59	0.02
Tunisia		0.01	0.09	0.15	0.89
Saudi Arabia	D(LnEnU(-1))	0.36	0.12	2.93	0.03
Tunisia		-0.68	0.12	-5.85	0.00
Saudi Arabia	D(LnTI)	0.04	0.02	2.41	0.04
Tunisia		0.03	0.02	1.86	0.08
Saudi Arabia	D(LnTI(-1))	0.07	0.02	2.94	0.03
Tunisia		-0.07	0.02	-3.35	0.00
Saudi Arabia	D(LnIVA)	-0.11	0.08	-1.38	0.23

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Tunisia		-0.46	0.10	-4.40	0.00
Saudi Arabia	D(LnIVA(-1))	0.13	0.11	1.22	0.28
Tunisia		-0.67	0.15	-4.31	0.00
Saudi Arabia	D(LnPoD)	-1.90	0.88	-2.17	0.05
Saudi Arabia	D(LnPoD(-1))	-2.19	0.93	-2.36	0.06
Saudi Arabia	D(LnTO)	0.14	0.07	2.05	0.06
Tunisia		0.27	0.06	4.72	0.00
Saudi Arabia	D(LnTO(-1))	-0.07	0.08	-0.84	0.44
Tunisia		0.23	0.09	2.65	0.02
Saudi Arabia	CointEq(-1)*	-0.42	0.07	-5.97	0.00
Tunisia		-1.11	0.13	-8.58	0.00

**p-value incompatible with t-Bounds distribution.*

4.5.3. Granger Causality Test

The Granger causality test assesses whether one time series can predict another by evaluating the statistical significance of lagged relationships. It identifies directional causality between variables, helping to uncover potential influences and dependencies in dynamic systems. The directional relationships between variables in the Saudi Arabia and Tunisia models, as shown in Table 10, reveal notable findings.

- LnEnU and LnCO2: For Saudi Arabia, LnEnU Granger-causes $LnCO_2$, with significance observed ($F = 3.39$, $p = 0.049$; $F = 4.83$, $p=0.017$) indicating a unidirectional causal relationship where energy use drives CO2 emissions. However, LnCO2 does not Granger-cause LnEnU ($p > 0.05$), suggesting no feedback effect.

- LnCO2 and LnPoD: For Tunisia, LnCO2 Granger-causes LnPoD significantly ($F = 15.05$, $p < 0.0001$), but no causality exists in the opposite direction. This suggests that CO2 emissions may influence population-related dynamics in Tunisia, such as migration or urbanization.

- LnTO and LnCO2: In Saudi Arabia, LnTO Granger-causes LnCO2 ($F = 3.80$, $p = 0.035$), showing that trade influences emissions, although this relationship is not significant in Tunisia ($p > 0.05$). The absence of reciprocal causality highlights trade's limited feedback on CO2 emissions.

- LnIVA and LnCO2: For Tunisia, LnIVA Granger-causes LnCO2 ($F = 7.68$, $p = 0.002$); however, this relationship weakens significantly in Saudi Arabia ($p > 0.05$). This underscores structural differences in the industrial contributions to emissions across the two countries.

- LnEnU and LnTI: In both countries, weak bidirectional Granger causality is observed between LnEnU and LnTI in some cases ($p = 0.0092$; $p = 0.044$), but this relationship diminishes in other instances ($p=0.09$), suggesting context-dependent interactions between energy use and industrialization.

The results underscore the dynamic and context-specific nature of causal relationships between energy, industry, trade, and CO2 emissions. In Saudi Arabia, energy use strongly influences CO2 emissions,

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while in Tunisia, CO2 emissions appear to drive population and trade dynamics. The divergence between datasets suggests the importance of model robustness and data accuracy when interpreting Granger causality relationships.

Table 10. Comparison of Granger Causality results

Null Hypothesis	Obs	F-Stat (Set 1) *	Prob. (Set 1)	F-Stat (Set 2)	Prob. (Set 2)
LnEnU does not Granger-cause LnCO2	31	3.385	0.049	4.827	0.017
LnCO2 does not Granger-cause LnEnU	31	0.346	0.711	1.621	0.217
LnTI does not Granger-cause LnCO2	25/31	1.055	0.367	2.275	0.123
LnCO2 does not Granger-cause LnTI	25/31	5.955	0.009	2.714	0.085
LnIVA does not Granger-cause LnCO2	32/31	7.682	0.002	0.248	0.782
LnCO2 does not Granger-cause LnTID	32/31	0.337	0.717	0.454	0.640
LnPOP does not Granger-cause LnCO2	32/31	1.243	0.305	1.273	0.297
LnCO2 does not Granger-cause LnPoD	32/31	0.867	0.432	15.046	0.0001
LnTO does not Granger-cause LnCO2	32/31	3.802	0.035	0.595	0.559
LnCO2 does not Granger-cause LnTO	32/31	0.312	0.735	2.220	0.129
LnTI does not Granger-cause LnEnU	24/31	0.330	0.723	0.099	0.906

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LnEnU does not Granger-cause LnTI	24/31	6.065	0.009	2.641	0.090

Note: set (1) denotes Saudi Arabia, set (2) denotes Tunisia.

5. DISCUSSION SECTION

This study investigates the dynamics of energy use and sustainability in Saudi Arabia and Tunisia, focusing on trade openness, industrialization, technological innovation, and population density. The results reveal distinct patterns influenced by each country's economic structure, resource endowments, and policy priorities.

For Saudi Arabia, energy use, technological innovation, and trade openness significantly contribute to CO2 emissions in the short term. This aligns with studies such as [34]; [35]; [36]; [9], which emphasize the environmental challenges posed by non-renewable energy use in fossil-fuel-dependent economies. However, the results also suggest that industrial value added has a negligible impact, diverging from findings in industrial economies like Turkey, where industrialization strongly drives emissions [17]. Additionally, the error correction term highlights a moderate adjustment speed toward equilibrium, reflecting Saudi Arabia's gradual policy shifts under Vision 2030.

Tunisia, by contrast, exhibits a faster adjustment speed, with energy use and trade openness playing critical roles in emissions dynamics. The observed mitigating effect of industrial value added on emissions supports findings by [4]; [37], which link industrial upgrades and green technologies to sustainability improvements. However, unlike Saudi Arabia, trade openness in Tunisia does not significantly influence emissions, suggesting limited trade-related environmental pressures. This discrepancy aligns with [38]; [39]; [40]; [23], who identified regional differences in trade's impact on sustainability.

The findings align with existing research highlighting the centrality of energy use in shaping environmental outcomes. Studies such as [40]; [41]; [42]; [20] corroborate the strong link between energy consumption and emissions, particularly in contexts with limited renewable energy adoption. In Saudi Arabia, the strong positive relationship is largely driven by its fossil fuel-reliant economy, where heavily subsidized domestic energy consumption and energy-intensive industries contribute to high emission levels. The dominance of oil and gas in electricity generation and industrial processes results in a direct correlation between energy use and environmental degradation. Conversely, Tunisia exhibits a more complex pattern. Although energy use still contributes to emissions, its reliance on energy imports and gradual shift toward renewables has incentivized more efficient consumption. Additionally, Tunisia's industrial modernization and trade openness appear to have a moderating effect on emissions, particularly as export-oriented industries adopt cleaner technologies to meet international standards. These differences underscore the role of structural and policy contexts, such as energy subsidies, trade composition, and industrial regulation, in shaping the energy-emissions nexus in resource-diverse economies. However, the results diverge from [22], who found that population density exacerbates emissions in densely urbanized areas. In this study, population density exhibits a complex relationship, with inconsistent short-term effects in Saudi Arabia and a mitigating influence in Tunisia. This suggests that the role of population dynamics in emissions is context-specific, influenced by factors such as urban planning and energy efficiency.

Furthermore, the study reinforces the importance of technological innovation in reducing emissions, aligning with findings by [43]; [44]; [8], who emphasize the transformative potential of green technologies. However, the negligible impact of industrialization in Saudi Arabia contrasts with global trends, suggesting that Saudi Arabia's industrial policies may not yet fully integrate sustainability considerations.

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These findings underscore the need for tailored sustainability strategies in each country. Accelerating the transition to renewable energy and integrating sustainability into industrial policies are critical to achieving Vision 2030 goals for Saudi Arabia. Fostering trade-related environmental regulations and enhancing energy efficiency are essential to balancing economic growth with ecological preservation for Tunisia. Future research should explore the interplay between policy interventions, regional cooperation, and technological advancements to build comprehensive sustainability models.

Recommendations for policymakers

The findings of this study offer significant insights for policymakers in Saudi Arabia and Tunisia as they strive to balance economic growth with environmental sustainability. Tailored strategies and interventions are essential to address the distinct challenges and opportunities in each country.

1. Saudi Arabia must prioritize diversifying its energy sources by investing in renewable energy infrastructure, aligning with Vision 2030's goals. Financial incentives such as subsidies and tax breaks for green energy technologies can accelerate this transition. Enhancing energy efficiency in industries and residential sectors is equally vital for mitigating emissions from energy use.

2. Industrialization in Saudi Arabia should integrate sustainability through clean technologies and energy-efficient practices. Policymakers can enforce stricter environmental regulations and offer incentives like green certifications and low-cost financing to encourage compliance. Supporting research and development can further drive innovation toward a circular economy.

3. Tunisia's trade openness offers opportunities to strengthen environmental standards. By complying with international regulations and pursuing green trade agreements, the country can promote sustainable practices in key sectors like agriculture and manufacturing, enhancing both environmental and economic outcomes.

4. Tunisia can further reduce emissions by modernizing its energy infrastructure to integrate renewables and improve demand-side management. Policymakers should also foster innovation by supporting green technology startups, enabling tailored solutions for the country's specific energy and environmental needs.

5. Urban planning plays a pivotal role in managing the environmental impacts of population density in both countries. Promoting smart city initiatives, energy-efficient buildings, and robust public transportation systems can reduce per capita emissions. Encouraging rural development programs can further alleviate urbanization pressures and ensure resource equity.

6. Collaboration between Saudi Arabia, Tunisia, and other MENA countries can facilitate knowledge sharing and joint initiatives. Regional platforms to exchange best practices in renewable energy and environmental policy, aligned with global frameworks like the Paris Agreement, can strengthen collective efforts toward sustainability.

7. Strengthening institutional capacity and fostering public awareness are crucial for sustainable development. Educational programs, public campaigns, and professional training can cultivate a culture of environmental responsibility while equipping stakeholders with the tools necessary to implement effective sustainability strategies.

6. CONCLUSIONS

This study explored the multifaceted relationships between energy use, trade openness, industrialization, technological innovation, population density, and environmental sustainability in Saudi Arabia and Tunisia. Key findings revealed that in Saudi Arabia, energy use and trade openness are significant contributors to CO_2 emissions, underscoring the challenges of reliance on fossil fuels. Conversely,

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Tunisia demonstrated a faster adjustment toward long-term equilibrium, with industrial modernization and trade-related factors mitigating emissions. These findings highlight the context-specific nature of sustainability drivers, emphasizing the distinct economic structures and policy environments of the two countries.

This research significantly contributes to understanding environmental sustainability in Saudi Arabia by identifying critical areas for policy intervention, including the adoption of renewable energy and the integration of sustainability into industrial frameworks. It also sheds light on Tunisia's unique strengths, such as its ability to leverage trade and industrial upgrades for environmental benefits. By employing ARDL models, the study offers valuable insights into both short-term and long-term dynamics, providing a robust basis for policymakers to design targeted strategies. While this study focuses on Saudi Arabia and Tunisia, its methodological framework and findings offer valuable insights for other resource-dependent and emerging economies. Countries facing the challenge of balancing industrial development, energy consumption, and environmental sustainability may find this model adaptable for formulating context-specific policy interventions.

Limitations of the study

This study, while comprehensive in its approach, acknowledges several limitations that provide avenues for future research. The study focuses on Saudi Arabia and Tunisia, its findings may not be fully generalizable to other MENA countries or global contexts due to variations in economic structures and policy frameworks. Additionally, the analysis aggregates data across broad sectors, potentially obscuring sector-specific dynamics, such as the distinct impacts of energy use in industrial versus residential contexts, thereby limiting the precision of policy recommendations. Population density is treated as a single variable, without distinguishing urban-rural disparities or considering the effects of migration and urban planning, which could provide more nuanced insights. Furthermore, the study relies primarily on quantitative methods, overlooking qualitative aspects such as public perceptions, institutional effectiveness, and cultural influences that play a significant role in shaping sustainability outcomes. Another limitation lies in the exclusion of qualitative institutional variables such as government environmental policies, regulatory enforcement, education, and socio-cultural norms. These factors often shape behavioral patterns and institutional effectiveness in implementing sustainable practices. Future research could employ a mixed-method approach or incorporate governance indices and survey data to explore these dimensions.

Future Research Directions

Future research should delve deeper into the role of technological innovation in accelerating sustainability transitions, particularly in resource-dependent economies like Saudi Arabia. Additionally, examining the interplay between urbanization and energy efficiency across diverse contexts can yield further insights. Comparative studies involving other MENA countries can also enhance regional cooperation and shared learning, fostering a collective move toward environmental resilience. This study lays the groundwork for advancing sustainability discourse and policymaking in the region, highlighting the critical balance between economic growth and ecological preservation.

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