Article

Not peer-reviewed version

Sustainability Under the Lens: A Comparative ARDL Analysis of Technology, Energy, Trade, and Industry in Saudi Arabia and Tunisia

Sonia Hedi Mannai *

Posted Date: 5 March 2025

doi: 10.20944/preprints202503.0292.v1

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

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 March 2025 doi:10.20944/preprints202503.0292.v1

Article

Sustainability Under the Lens: A Comparative ARDL Analysis of Technology, Energy, Trade, and Industry in Saudi Arabia and Tunisia

Sonia Mannai

Department of Finance and Investment, Faculty of Business Administration, University of Tabuk, Tabuk 71491, KSA. PS2D, FSEG Tunis -University Tunis El Manar; s_almanae@ut.edu.sa

Abstract: This study investigates the dynamics between energy consumption, 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 1991 to 2023. 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. The study contributes to the comparative literature on sustainability, providing valuable insights for policymakers and researchers aiming to balance economic growth with environmental preservation in resource-diverse economies.

Keywords: sustainability; energy use; trade; industrialization; population density; technology; ARDL; Saudi Arabia; Tunisia; CO2 emissions

---

1. Introduction

Environmental sustainability has become a pressing global concern, especially as nations grapple with the dual challenges of economic development and ecological preservation. The intersection of technological innovation, energy consumption, trade openness, and industrialization play a pivotal role in shaping environmental outcomes. However, the impacts of these factors are not uniform across countries, as they are influenced by unique economic structures, resource endowments, and policy priorities. Understanding these dynamics in diverse contexts is critical for formulating effective strategies to achieve sustainable development.

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.

Technological innovation serves as a double-edged sword in the sustainability discourse. While it has the potential to 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 but manifests differently: Saudi Arabia's reliance on fossil fuels contrasts sharply with Tunisia's growing focus on energy diversification and renewable sources.

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

2.1. The Environmental Kuznets Curve (EKC) and Sustainability

The Environmental Kuznets Curve (EKC) hypothesis is a widely accepted framework for understanding the interplay between economic growth and environmental degradation. It posits that environmental damage increases during the initial stages of economic growth but declines after reaching a certain income threshold as economies adopt cleaner technologies and better policies. [1] confirmed this hypothesis for OECD countries, demonstrating that renewable energy and financial development play pivotal roles in reducing ecological footprints. Similarly, [2] validated the EKC in Saudi Arabia, where urbanization and industrialization were shown to increase CO_2 emissions. However, they observed that higher incomes and structural transformations, as anticipated under the EKC, could lead to reduced emissions.

In developing economies, the relationship varies. Likewise, [3] found in Bangladesh that CO_2 emissions rise alongside economic growth, with emissions only declining when renewable energy and green technologies are implemented at scale. For Tunisia, no direct study confirms the EKC, but evidence from similar economies highlights the importance of aligning economic and environmental policies to achieve sustainable development [4].

2.2. 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

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 March 2025 doi:10.20944/preprints202503.0292.v1

enhancing energy efficiency and promoting cleaner industrial processes. [5] 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, [6] demonstrated how digital transformation and innovation in financial systems have improved sustainability metrics, particularly when coupled with strong regulatory frameworks.

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 [7].

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 [8,9]. For Tunisia, expanding innovation in renewable technologies could address existing gaps in energy efficiency and industrial emissions [10].

2.3. 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. Refs. [11,12] 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. [13] 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.

In the context of global efforts to align energy use with sustainable development goals (SDGs), renewable energy has emerged as a key focus area. [14] 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, [15] 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 has garnered attention in recent studies. [16] 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.

2.4. 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

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 March 2025 doi:10.20944/preprints202503.0292.v1

the mixed outcomes of TO, stressing the importance of aligning trade policies with sustainable development goals.

2.5. 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 [3,9].

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 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.

Despite the growing body of literature on environmental sustainability, significant gaps remain, particularly in the contexts of Saudi Arabia and Tunisia. Comparative studies that analyze how distinct economic structures influence sustainability outcomes are scarce, with most research focusing on single-country analyses. The long-term impacts of trade openness and its interaction with industrialization and environmental outcomes in resource-rich and developing economies remain ambiguous. Furthermore, while technological innovation and renewable energy adoption are recognized as critical to sustainability, limited attention has been given to the challenges faced by emerging economies in leveraging these effectively, particularly under differing financial and governance conditions. Studies often neglect the dual role of industrialization as both a growth driver and an environmental stressor, as well as the transitional challenges in shifting from fossil fuels to

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 March 2025 doi:10.20944/preprints202503.0292.v1

renewable energy, especially in resource-dependent nations like Saudi Arabia. Additionally, research frequently examines individual factors—such as trade, energy, or industrialization—in isolation, lacking an integrated approach to understanding their collective impact. There is also insufficient focus on the geopolitical and regional dimensions of sustainability, such as shared resource management and regional cooperation, alongside a limited exploration of long-term policy impacts using dynamic econometric models like ARDL. This study addresses these gaps by providing a comprehensive and comparative analysis of the determinants of environmental sustainability in 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).
- 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).

3.2. ARDL Model Justification

The Autoregressive Distributed Lag (ARDL) model is employed to analyze the relationships between the variables for several reasons, first; ARDL can handle variables that are integrated of order zero, I(0), or order one, I(1), without requiring all variables to be of the same order. Second; the ARDL model allows for the simultaneous estimation of short-term and long-term relationships between the dependent and independent variables. Third; given the relatively short time frame of the dataset, the ARDL model is well-suited to producing reliable estimates. Fourth; the ARDL bounds testing approach identifies a long-run equilibrium relationship among the variables, even with a limited dataset.

Model Specification

The study employs the ARDL model to investigate the short- and long-run relationships between CO_2 emissions and its determinants, including GDP, trade openness, energy consumption, technological innovation, and industrialization. The ARDL approach, introduced by [25], 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 consumption and trade openness often exhibit mixed stationarity [26]. 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

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 March 2025 doi:10.20944/preprints202503.0292.v1

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 [27] 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 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 Oxide emission in Saudi Arabia.
- TCO_{2it} is the Carbon Oxide 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 Consumption for both countries.
- TI_{it} is Technological Innovation for both countries.
- IVA_{it} is Industry Value Added for both countries.
- PoD_{it} is population density for both countries.

After taking the first differentiation, equation (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:

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

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 $\phi 2 \neq 0$).

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).

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

where:

- ΔYt: Change in the dependent variable (CO_2 emissions).

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 March 2025 doi:10.20944/preprints202503.0292.v1

- ΔX_{t-j}: Change in the independent variables (GDP, trade openness, energy use, technological innovation, and industry value added, and population density).
- α_0: Constant term.
- β_i, γ_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.

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 CO2 emissions (LnCO2: 2.5738 vs. 0.8096), energy consumption (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 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 show 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

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 March 2025 doi:10.20944/preprints202503.0292.v1

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.

Table 2. Saudi 'correlation matrix**.**

	LNCO₂	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**.**

	$LNCO_2$	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 Squire (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 consumption (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
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.

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					
Saudi Arabia	LnPoD	-3.65	-2.95	-2.62	-2.69	0.09	-3.65	-2.96	-2.62	-0.50	0.88	**-3.66**	**-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. Vector Autoregression Model (VAR)

Table 6 presents the results of lag order selection criteria for VAR models for Saudi Arabia and Tunisia, based on key statistical measures including LogL (log-likelihood), LR (likelihood ratio), FPE (final prediction error), AIC (Akaike information criterion), SC (Schwarz criterion), and HQ (Hannan-Quinn criterion). The asterisks (*) indicate the selected lag order based on the lowest value for each criterion. For Saudi Arabia, lag 1 is the optimal lag length as it minimizes FPE, AIC, SC, and HQ, while showing a significant likelihood improvement over lag 0. For Tunisia, lag 2 is the optimal choice, indicated by the lowest FPE, AIC, SC, and HQ values, and a significant LR statistic compared to lag 1. These selected lags provide the best balance between model fit and complexity for VAR modeling in each country.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 March 2025 doi:10.20944/preprints202503.0292.v1

Table 6. VAR lag order selection criteria.

Country	Lag	LogL	LR	FPE	AIC	SC	HQ
Saudi Arabia	0	134.39190	NA	0.00000	-9.51051	-9.22255	-9.42488
Tunisia		228.4766	NA	2.35E-14	-14.35333	-14.07579	-14.26286
Saudi Arabia	1	338.96090	303.0652*	1.21e-17*	-21.99711*	-19.98136*	-21.39772*
Tunisia		416.9292	291.7975	1.32E-18	-24.18898	-22.24616	-23.55567
Tunisia	2	504.8225	102.0697*	6.16e-20*	-27.53694*	-23.92884*	-26.36079*

* indicate the selected lag order based on each criterion.

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)	Eigenvalue	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
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 [28]. p-values.

4.5.2. Error Correction Model

The ARDL results in Table 8 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

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 March 2025 doi:10.20944/preprints202503.0292.v1

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 8. ECM regression results**.**

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
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 9 revealing notable findings.

- LnEnU and LnCO2: For Saudi Arabia, LnEnU Granger-causes LnCO2, 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, while in Tunisia, CO2 emissions appear to drive population and trade dynamics. The

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 March 2025 doi:10.20944/preprints202503.0292.v1

divergence between datasets suggests the importance of model robustness and data accuracy when interpreting Granger causality relationships.

Table 9. 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
LnEnU does not Granger Cause LnTI	24/31	6.065	0.009	2.641	0.090

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

5. Discussion Section

This study investigates the dynamics of environmental sustainability in Saudi Arabia and Tunisia, focusing on energy use, 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 [15,29–31], 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 [4,32], 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 [23,33–35], 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 [20,36–38] corroborate the strong link between energy consumption and emissions, particularly in contexts with limited renewable energy adoption. 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 [14,39,40], who emphasize the transformative potential of green technologies. However, the negligible impact of industrialization in Saudi Arabia contrasts with

 doi:10.20944/preprints202503.0292.v1

global trends, suggesting that Saudi Arabia's industrial policies may not yet fully integrate sustainability considerations.

These findings underscore the need for tailored sustainability strategies in each country. For Saudi Arabia, accelerating the transition to renewable energy and integrating sustainability into industrial policies are critical to achieving Vision 2030 goals. For Tunisia, fostering trade-related environmental regulations and enhancing energy efficiency are essential to balancing economic growth with ecological preservation. 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, 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 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.

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.

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.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The author declares no conflict of interest.

References

1. WANG, Shubin; LI, Jian; RAZZAQ, Asim. Do environmental governance, technology innovation and institutions lead to lower resource footprints: An imperative trajectory for sustainability. *Resources Policy*, **2023**, 80: 103142.
2. AHMED, Zahoor, et al. How do green energy technology investments, technological innovation, and trade globalization enhance green energy supply and stimulate environmental sustainability in the G7 countries?. *Gondwana Research*, **2022**, 112: 105-115.
3. RAIHAN, Asif, et al. The influence of Information and Communication Technologies, Renewable Energies and Urbanization toward Environmental Sustainability in China. *Journal of Environmental and Energy Economics*, **2022**, 1.1: 11-23.
4. Pata, U. K., & Isik, C. Determinants of the load capacity factor in China: a novel dynamic ARDL approach for ecological footprint accounting. *Resources Policy*, **2021**, *74*, 102313.

5. DEROUEZ, Faten; IFA, Adel; AL SHAMMRE, Abdullah. Energy Transition and Poverty Alleviation in Light of Environmental and Economic Challenges: A Comparative Study in China and the European Union Region. *Sustainability*, **2024**, 16.11: 4468.
6. KARLILAR, Selin; BALCILAR, Mehmet; EMIR, Firat. Environmental sustainability in the OECD: The power of digitalization, green innovation, renewable energy and financial development. *Telecommunications Policy*, **2023**, 47.6: 102568.
7. CHEN, Xiaoxia; DESPEISSE, Mélanie; JOHANSSON, Björn. Environmental sustainability of digitalization in manufacturing: A review. *Sustainability*, **2020**, 12.24: 10298.
8. SUMON, Md Fakhrul Islam, et al. Environmental and socio-economic impact assessment of renewable energy using machine learning models. *Journal of Economics, Finance and Accounting Studies*, **2024**, 6.5: 112-122.
9. Sohag, K., Begum, R. A., Abdullah, S. M. S., & Jaafar, M. Dynamics of energy use, technological innovation, economic growth and trade openness in Malaysia. *Energy*, 2015, *90*, 1497-1507.DOI: 10.1016/j.energy.2015.05.091.
10. PATA, Ugur Korkut; KARLILAR PATA, Selin. Towards sustainable development in African countries: Are modern and combustible renewable energies effective?. *Sustainable Development*, **2024**.DOI: 10.1002/sd.3040.
11. Zhang, J., Muhammad, T., Dai, W., Khan, Q. R., & Ahmad, M. How Does the Resource Curse Influence Economic Performance? Exploring the Role of Natural Resource Rents and Renewable Energy Consumption in South Asia. *Sustainability*, (2024), *16*(24), 11138.
12. RAIHAN, Asif. The influence of tourism on the road to achieving carbon neutrality and environmental sustainability in Malaysia: The role of renewable energy. *Sustainability Analytics and Modeling*, 2024, 4: 100028.
13. Gyawali, M., & Sharma, B. *Unveiling the Complexities of Economic, Development, and Governance Factors in Belt and Road Countries*. Sustainable Development Review, **2025**. 47(3), 203-218.
14. Demirkale, O., & Duran, N. I. (China's Sustainable Development under Climate, Energy and Policy Uncertainty: A Focus on SDG 7 and SDG 13. *International Journal of Energy Economics and Policy*, **2025**, *15*(1), 532-540.
15. Shaheen, R., & Gardezi, Z. *Nexus Between Green Resources, Energy Consumption, and Environmental Quality in Pakistan*. Renewable Energy and Environment, **2024**, 34(6), 456-470.
16. Ibrahim, K., & Ahmed, M. (2024). *Natural Resources Heterogeneity and Environmental Sustainability in G20 Nations*. Environmental Economics and Policy Studies, 29(2), 211-234.
17. Dam, M. M., & Sarkodie, S. A. Renewable energy consumption, real income, trade openness, and inverted load capacity factor nexus in Turkiye: Revisiting the EKC hypothesis with environmental sustainability. *Sustainable Horizons*, **2023**, *8*, 100063. DOI: 10.1016/j.horiz.2023.100017.
18. Sarkodie, S. A., & Strezov, V. Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. *Science of the total environment*, 2019, *646*, 862-871.
19. Haraguchi, N., Martorano, B., & Sanfilippo, M. What factors drive successful industrialization? Evidence and implications for developing countries. *Structural Change and Economic Dynamics*, **2019**, *49*, 266-276.
20. Miassi, Y. E., Akdemir, S., & Dossa, K. F. Investigating global warming's influence on food security in Benin: in-depth analysis of potential implications of climate variability on maize production. *Journal of Taibah University for Science*, **2024**, *18*(1), 2316361.
21. Vukmirović, V., Kojić, M., Spasenić, Ž., & Milosavljević, M. How do socio-demographic factors affect green finance growth?. *Stanovništvo*, 2024, *62*(2), 211-230.
22. Alqaralleh, H. Bricks and sustainability: a look at how environmental variables impact housing markets. *International Journal of Housing Markets and Analysis*., **2024**.
23. Mata, J. P. V., Bautista, M. G. G., Granda, L. E. S., & Moreano, E. G. Z. Evaluating the Environmental Kuznets Curve: The Role of Renewable Energy, Economic Growth, Urban Density and Trade Openness on CO2 Emissions. An Analysis for High-Income Countries Using the CS-ARDL Model. *International Journal of Energy Economics and Policy*, **2024**, *14*(6), 580-596.

24. Oprea, S. V., Bâra, A., & Georgescu, I. A. Assessing the Dynamics of Ecological Footprint in Relation to Economic and Energy Factors: A Comparative Analysis of Finland and Japan. *Journal of the Knowledge Economy*, **2024**, 1-36.
25. Pesaran, M. H., Shin, Y., & Smith, R. J. Bounds testing approaches to the analysis of level relationships. *Journal of applied econometrics*, **2001**, *16*(3), 289-326. DOI: 10.1002/jae.616.
26. Solarin, S. A., & Shahbaz, M. Trivariate causality between economic growth, urbanisation and electricity consumption in Angola: Cointegration and causality analysis. *Energy policy*, **2013**, *60*, 876-884.
27. Al-Mulali, U.; Sheau-Ting, L.; Ozturk, I. The global move toward Internet shopping and its influence on pollution: an empirical analysis. *Environmental Science and Pollution Research*, **2015**, 22, 9717-9727.
28. MacKinnon, J.G.; Haug, A.A.; Michelis, L. Numerical Distribution Functions of Likelihood Ratio Tests for Cointegration. J. Appl. Econom. 1999, 14, 563–577. http://dx.doi.org/10.1002/(SICI)1099-1255(199909/10)14:53.0.CO;2-R.
29. Mohammed, M. G. A., Abdel-Gadir, S. E. M., Alsulami, F., Mannai, S., Arfaoui, L., Alharbi, K., ... & Alsafy, M. M. Exploring the Effects of Renewable Energy, Energy Consumption, and Industrial Growth on Saudi Arabia's Environmental Footprint: An Autoregressive Distributed Lag Analysis. *Energies*, 2024, *17*(24), 6327.
30. Barkat, K.; Alsamara, M.; Al Kwifi, O. S.; Jarallah, S. Does trade openness mitigate environmental degradation in Organisation for Economic Co-operation and Development (OECD) countries? Implications for achieving sustainable development. Natural Resources Forum **2024**, Blackwell Publishing Ltd.
31. Bouchoucha, N. Does trade openness and environmental quality matter for health status? Evidence from African countries. Journal of the Knowledge Economy **2024**, 15(2), 5729-5745.
32. Ali, S. R., & Mujahid, N. Sectoral carbon dioxide emissions and environmental sustainability in Pakistan. *Environmental and Sustainability Indicators*, **2024**, *23*, 100448.
33. Wang, Q., & Zhang, F. The effects of trade openness on decoupling carbon emissions from economic growth–evidence from 182 countries. *Journal of cleaner production*, **2021**, *279*, 123838.
34. Omri, A., Daly, S., Rault, C., & Chaibi, A. *Financial development, environmental quality, trade, and economic growth: What causes what in MENA countries?*. Energy Economics, **2015**, 48, 242-252. DOI: 10.1016/j.eneco.2015.01.008
35. Mata, J. P. V., Bautista, M. G. G., Granda, L. E. S., & Moreano, E. G. Z. Evaluating the Environmental Kuznets Curve: The Role of Renewable Energy, Economic Growth, Urban Density and Trade Openness on CO2 Emissions. An Analysis for High-Income Countries Using the CS-ARDL Model. *International Journal of Energy Economics and Policy*, **2024**, *14*(6), 580-596.
36. Posu, S. M. A., Fapetu, O., Dada, M. A., Ojo, O. T., & Adeniyi, A. I. Urbanization, energy use, and carbon dioxide emissions linkage in Nigeria: Evidence from auto-regressive distributed lag bound approach. *Fuoye Journal of Finance and Contemporary Issues*, **2024**, *6*(1).
37. Bousrih, J. The nexus between economic growth, urbanization, technological advancement, and CO2 emissions: Where does the GCC stand? Asian Journal of Economic Modelling **2024**, 12(3), 190-202.
38. Brahmia, S. Y., & Mannai, S. Environmental Degradation in GCC: Role of ICT Development, Trade, FDI, and Energy Use, **2024**.
39. Coban, S.; Ulusay, N.; Doğan, T. Analysis of the Impact of Internet Use, Energy Consumption and Economic Growth on CO2 Emissions: Evidence from OECD Countries. **2022**.
40. Bekun, F. V., Emir, F., & Sarkodie, S. A. Another look at the relationship between energy consumption, carbon dioxide emissions, and economic growth in South Africa. *Science of the Total Environment*, **2019**, *655*, 759-765.