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Article

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Navigating the Oil-environment Nexus: Saudi Arabia's Challenge in Sustainable Development

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ABSTRACT

This paper delves into Saudi Arabia's challenge of aligning its substantial oil production with environmental sustainability goals, particularly within the framework of Vision 2030. Utilizing an Autoregressive Distributed Lag (ARDL) approach, it examines data from 1980 to 2022, analyzing the relationships between oil production, economic growth, CO_2 emissions, and environmental regulation compliance. The study highlights the intricate dynamics between oil-driven economic development and environmental conservation, revealing significant long-term correlations that underscore the environmental costs accompanying economic benefits derived from oil. These findings illuminate the delicate balance Saudi Arabia faces, pointing to the need for sustainable practices in the oil industry and diversified economic growth. The research provides strategic insights for policy formulation, aiming to harmonize economic prosperity with environmental health. This work contributes significantly to the discourse on sustainable development in resource-rich economies, offering a vital perspective on managing natural resources responsibly while pursuing economic growth.

Keywords: Saudi Vision 2030, Environmental Sustainability, Oil Production, Energy Policy, Economic Growth, CO_2 Emissions
JEL Classifications: Q53, Q43, O13, Q54, E23, O44

1. INTRODUCTION

The increasing levels of carbon dioxide (CO_2) in the atmosphere have emerged as a pressing environmental challenge due to their significant contribution to global warming (Leonel, 2023). CO_2, as the most prevalent greenhouse gas (GHG), is experiencing a rapid increase, with concentrations growing at a rate exceeding 2 ppm per year (Ramirez-Corredores et al., 2023). Various efforts have been initiated to address this issue, including developing carbon capture and storage technologies designed to capture CO_2 emissions from industrial process and sequester them underground (Krishnan and Jakka, 2022). Furthermore, promising advancements have been in utilizing CO_2 as a feedstock for producing intermediate chemicals, offering a dual solution of mitigating emissions and reducing reliance on fossil fuels (Krishnan et al., 2021) (Simmons, 2021). This growing global concern over CO_2 emissions and its relationship to climate change has resulted in ambitious initiatives such as "Net-Zero" objective to prevent global warming to 1.5°C by 2050. It underscores the need to reduce CO_2 emissions and explore alternative energy sources to secure a sustainable future for the planet and future generations.

Understanding the intricate interplay between oil production, economic activities, and CO_2 emissions is paramount in comprehending the environmental implications of industrialization and energy consumption. This nexus assumes particular importance in the context of Saudi Arabia, a nation endowed with abundant oil resources and heavily reliant on economic activities associated with oil production. The essence of these matters in the Saudi Arabian context is underscored by their far-reaching consequences for climate change mitigation and sustainable development. Emerging findings indicate that urbanization, energy consumption, industrialization, and foreign direct investments affect the intensity of carbon emissions (CEI) (Orin, 2023). Moreover, evidence points to a bidirectional causality between CO_2 emissions and economic growth, alongside a feedback hypothesis between trade openness and CO_2 emissions (Naif and Amirah, 2022). Proposals for a circular carbon economy model and digitalization have been put forward as pathways to mitigate CO_2 emissions and achieve sustainability objectives (Daly and Abdouli, 2023). Financial development and adopting renewable energy have also been identified as pivotal policy variables for reducing carbon emissions and promoting sustainable development (Nadia et al., 2023; Samargandi, 2017).

The research objectives of this study are to investigate the complex interplay between various economic factors and carbon dioxide (CO_2) emissions in Saudi Arabia, with a focus on the roles played by total primary energy consumption, oil production, agriculture, forestry, and fishing value-added, GDP and industry value added. Specifically, the study aims to assess the drivers of CO_2 emissions in the country, evaluate the effectiveness of environmental policies, and propose strategies for reducing carbon emissions while achieving sustainable economic growth. Additionally, the research seeks to understand the implications of Saudi Arabia's Vision 2030 initiative in the context of CO_2 emissions reduction and sustainable development.

This research enriches the current knowledge by investigating the intricate connections between economic factors, energy consumption, and carbon dioxide (CO_2) emissions in Saudi Arabia, providing valuable empirical insights specific to this oil-rich nation. Moreover, it assesses the effectiveness of Saudi Arabia's Vision 2030 sustainability initiatives in reducing CO_2 emissions and fostering economic diversification, offering a comprehensive evaluation that can serve as a benchmark for policymakers. The study's findings inform policy decisions by highlighting the drivers of CO_2 emissions and their interplay with economic activities, emphasizing the importance of renewable energy investments, and advocating for a balanced approach to oil production. These insights guide formulating policies geared towards economic diversification, renewable energy adoption, and environmental sustainability, ultimately supporting Saudi Arabia's transition to a more sustainable and diversified economy while addressing its Vision 2030 objectives.

2. LITERATURE REVIEW

The literature review focuses on Saudi Arabia's economic activities and carbon dioxide emissions. It will examine the complex relationships between GDP, industrialization, energy use and CO_2 emissions trends in the country. The review seeks to understand emissions drivers, evaluate environmental policies, and suggest ways to reduce carbon emissions and achieve sustainable economic growth.

2.1. CO_2 Emissions in Saudi Arabia

Energy consumption, industrialization, urbanization, and economic development have affected Saudi Arabia's CO_2 emissions trends. Alshehry and Belloumi (2015) found that the rising GDP share of manufacturing and heavy industries has driven CO_2 emissions. Short-term economic and demographic changes have also increased CO_2 emissions (Köne and Büke, 2010). Urbanization increased continuously throughout the sample period, affecting CO_2 emissions (Mahmood et al., 2020). However, CO_2 emissions have suddenly decreased, demonstrating the complexity of Saudi Arabia's emissions factors (Raggad, 2020). Due to Saudi Arabia's oil industry and carbon emissions, CO_2 emissions trends have global implications (Alkhathlan and Javid, 2015).

Oil production influences greenhouse gas emissions (Van Ruijven and Van Vuuren, 2009). Different regions' conventional oil sands and tight oil production have caused different greenhouse gas emissions (Yeh et al., 2010). Oil production, energy consumption, and economic growth in oil-producing countries affect greenhouse gas emissions (Yusuf et al., 2020). The environmental effects of unconventional heavy oil production and future natural gas greenhouse gas emissions should also be considered (Crow et al., 2019; Nduagu and Gates, 2015; Chen et al., 2019).

Oil production releases greenhouse gases like carbon dioxide and methane, which have long-term environmental effects (El-Houjeiri et al., 2013). Oil production energy intensity and emissions have been studied to estimate and mitigate greenhouse gas impacts (Brandt et al., 2016; Ike et al., 2020). Oil and gas production greenhouse gas emissions aggregation and allocation and their effects on life-cycle greenhouse gas burdens are debated (Waxman et al., 2020).

In conclusion, economic, industrial, and urbanization factors affect Saudi Arabia's CO_2 emissions trends. Addressing the environmental impact of the country's economic development and implementing effective mitigation strategies requires understanding these trends.

2.2. Economic Factors Influencing CO_2 Emissions

Environmental economics has extensively studied the relationship between total primary energy consumption and CO_2 emissions. Many studies have studied the intricate relationship between energy consumption, CO_2 emissions, and economic growth worldwide.

European, Chinese, Gulf Cooperation Council and Turkish empirical evidence show a long-term relationship between energy consumption and CO_2 emissions. CO_2 emissions rise with energy consumption, according to the findings. This relationship affects climate change mitigation and environmental sustainability.

Urbanization's effects on energy use and CO_2 emissions have been studied, particularly in China (Benlaria et al., 2023). Urbanization increases energy consumption and CO_2 emissions, highlighting the need for sustainable urban development and energy-efficient infrastructure.

Despite some disagreements about the magnitude of the relationship between energy consumption and CO_2 emissions, most agree that they are linked. This relationship emphasizes switching to renewable and clean energy to reduce CO_2 emissions and climate change.

Studies show that oil production in oil-producing countries affects the nexus of CO_2 emissions (Ebohon and Ikeme, 2006; Zakari et al., 2022). The energy intensity of crude oil production and high-level gas flaring have raised CO_2 levels (Masnadi and Brandt, 2017). Unemployment and greenhouse gas emissions in oil-producing regions have also raised concerns (Isola and Mesagan, 2014).

The effects of "peak oil" on CO_2 and climate have also been studied (Kharecha and Hansen, 2008). If oil production peaks in the next few decades, it may affect future CO_2 levels. Oil extraction from oil sands causes forest loss, water use, and CO_2 emissions, raising concerns about its sustainability (Rosa et al., 2017).

The economic benefits of oil production are debated, but the long-term environmental impacts are crucial (Al-Saleh et al., 1991). Asymmetry analysis of the oil sector and CO_2 emissions in oil-producing countries shows the complex relationship between oil production, urbanization, and CO_2 emissions (Mahmood et al., 2020). This requires a balanced approach to oil production's environmental, economic, and social impacts.

Saudi Arabian CO_2 emissions are influenced by agriculture, forestry, fishing, and industry. Environmental damage from agricultural production, particularly date production, increases CO_2 emissions (Abda and Emam, 2022). Industrialization, foreign direct investments, and technological innovation decrease carbon emissions intensity (CEI) in most quantiles, suggesting that industry sector CO_2 emissions can be reduced (Orin, 2023). Industrial processes and product use (IPPU)—including petrochemical, steel, and cement production-is a major CO_2 emitter in the Kingdom (Muhammad et al., 2022). The energy, activity, and population effects are the main greenhouse gas emission factors in various sectors, with the electricity sector having a more significant impact than transport (Alajmi, 2021). These findings show that Saudi Arabia needs green policies, renewable energy, and energy efficiency to reduce CO_2 emissions and achieve sustainable development (Aziz et al., 2023).

In conclusion, studying the relationship between total primary energy consumption and CO_2 emissions is crucial for environmental sustainability and climate change. Understanding this relationship is crucial for policymaking and accelerating the low-carbon energy transition.

2.3. Vision 2030 Sustainability Strategies

The Saudi Arabia Vision 2030 initiative aims to achieve economic diversification and reduce dependency on oil (Elbanna, 2023). This vision aims to increase non-oil exports from 16% to 50% of non-oil GDP by 2030 (Hasanov & Razek, 2023). To enhance future productivity and economic competitiveness, a range of initiatives, including those led by the Public Investment Fund (PIF), are necessary (Fakhri et al., 2023). The strategic framework prioritizes the localization of production processes to reduce dependence on imports, encouraging the growth of domestic goods and services, and fostering local content development to enhance economic diversification (Nahla et al., 2023). The plan acknowledges the significance of foreign investment and technology in enhancing economic, financial, and social infrastructures and fostering a favorable environment for business (Fardien et al., 2023). The plan prioritizes economic diversification, yet it overlooks environmental concerns and fails to address oil production optimization.

The Vision 2030 initiative commits to mitigating CO_2 emissions by reducing fossil fuel consumption and allocating resources towards renewable energy sources. This entails establishing renewable energy centers that utilize essential mineral resources to produce and function renewable energy technologies (Tarifa et al., 2023). The strategic blueprint additionally maximizes the utilization of mineral resources in order to bolster the achievement of the nation's renewable energy objectives. The objective is to promote investments in sustainable energy sources and expedite the shift towards renewable energy generation, specifically solar energy, to stimulate economic advancement and mitigate carbon emissions (Hasanov & Razek, 2023). The nation aims to achieve sustainable economic growth by diminishing reliance on fossil fuels and augmenting non-oil exports (Fakhri et al., 2023; Benlaria and Hamad, 2022). This alignment highlights the correlation between economic diversification and environmental sustainability.

The strategic narrative advocates for implementing financial and renewable energy policies to mitigate carbon emissions and foster sustainable development, moving away from reliance on oil (Lumin et al., 2023). According to Fakhri et al. (2023), the advancement of financial systems and the adoption of renewable energy technologies decrease carbon emissions. Conversely, economic growth and the exploitation of natural resources tend to increase carbon emissions. The plan highlights the significance of foreign investment and assets in promoting technological advancement and enhancing economic, financial, and social infrastructures to enhance competitiveness and sustainability (Hasanov & Razek, 2023; Houcine et al., 2023). Energy intensity and CO_2 emissions can be reduced through economic diversification away from hydrocarbons and implementing fiscal and energy pricing reforms. Nevertheless, the successful execution of these strategies requires a competitive institutional framework.

3. DATA AND METHODOLOGY

3.1. Variables and Data Source

This study employs a comprehensive dataset covering the period from 1980 to 2022. The data compiled from various reputable sources, as summarized in Table 1, are integral to the empirical analysis.

Table 1: Data series overview

Series name	Abbreviation	Source
CO_2 emissions (kt)	CO_2	ourworldindata.org
Total primary energy consumption	EC	public.knoema.com
Oil production (TWh)	OP	ourworldindata.org
Agriculture, forestry, and fishing, value added	AGR	databank.worldbank.org
GDP (current US$)	GDP	databank.worldbank.org
Industry (including construction), value added	IND	databank.worldbank.org

Each data series has been carefully selected for its reliability and relevance to the research objectives. It ensures a robust econometric analysis of the interplay between economic growth, energy consumption and environmental outcomes.

3.1.1. CO_2 emissions

Carbon dioxide emissions quantified in kilotonnes (kt) represent the total emissions from the combustion of fossil fuels and cement production, covering energy sources such as solid, liquid, and gas fuels, in addition to gas flaring. This data is a critical measure of a country's environmental impact, particularly concerning global warming and climate change.

The dataset for CO_2 emissions is sourced from Our World in Data, a comprehensive resource that provides extensive historical environmental and energy-related data, ensuring a robust foundation for empirical analysis.

3.1.2. Total primary energy consumption

The Total Primary Energy Consumption encompasses the sum of energy sources a nation uses, including non-renewable resources like oil, coal, natural gas, and renewable energy sources. It reflects the full energy required to support a nation's economy and is an essential indicator for understanding energy demand and energy use intensity.

This data is retrieved from Knoema, a global repository that consolidates figures from various international and national databases, providing a comprehensive view of energy consumption patterns worldwide.

3.1.3. Oil production (TWh)

Oil production data, measured in terawatt-hours (TWh), quantifies the total energy generated from crude oil extraction. This metric is pivotal for evaluating the scale of the oil industry's output and its contribution to the national and global energy supply.

The oil production figures are collected from Our World in Data, which aggregates global energy production statistics and provides a historical perspective on energy trends.

3.1.4. Agriculture, forestry, and fishing, value added (current US$)

This variable shows the net output of ISIC divisions 1-3 agriculture, forestry, and fisheries. Forestry, hunting, fishing, crop production, and livestock production are included. The International Standard Industrial Classification (ISIC), revision 4, defines value added as the sector's economic contribution without deductions for asset depreciation or natural resource depletion and degradation.

Data on value added by agriculture, forestry, and fishing are obtained from the World Bank database in current U.S. dollars, providing an internationally comparable measure of sectoral economic performance.

3.1.5. Industry (including construction), value added (current US$)

In ISIC divisions 05-43, industry includes construction and other economic activities. This category reflects value contributed in mining, manufacturing, construction, power, water, and gas utilities (ISIC divisions 10-33). According to the International Standard Industrial Classification (ISIC), version 4, value added for this sector is calculated by combining outputs and subtracting intermediate inputs to get the net output without asset depreciation or natural resource depletion.

Current U.S. dollar figures for the industry's value-added are sourced from the World Bank database, which provides a consistent and comparative economic analysis framework.

3.1.6. GDP (current US$)

GDP at purchaser's prices is the sum of all resident producers' gross value added, adjusted for product taxes and subsidies not included in product value. The data reflects a country's economic performance, calculated in current U.S. dollars, providing a snapshot of its economic size and health without accounting for depreciation or resource depletion. GDP figures are converted using official exchange rates, and alternative factors are used where official rates do not reflect the actual rates applied to transactions.

The World Bank database is the source of this data, ensuring that the figures are internationally comparable and consistent.

3.2. Methodology: Autoregressive Distributed Lag (ARDL) Approach

We use Autoregressive Distributed Lag (ARDL) co-integration to simulate the dynamic link between CO_2 emissions and economic and energy consumption components in this study. The ARDL model is specified as in "Eq. (1)"

$$\Delta\log(\mathrm{CO2}_t)=\alpha+\sum_{i=1}^{P}\beta_i\Delta\log(\mathrm{CO2}_{t-i})+\sum_{i=0}^{q}\gamma_{1i}\Delta\log(OP_{t-i})+\sum_{i=0}^{q}\gamma_{2i}\Delta\log(GDP_{t-i})+\sum_{i=0}^{q}\gamma_{3i}\Delta\log(IND_{t-i})+\sum_{i=0}^{q}\gamma_{4i}\Delta\log(AGR_{t-i})+\sum_{i=0}^{q}\gamma_{5i}\Delta\log(EC_{t-i})+\lambda\mathrm{ECM}_{t-1}+\in_{\mathrm{t}} \quad (1)$$

Here, Δ the first difference operator α is the constant term, $\beta_i \gamma ji$ the short-run dynamic coefficients, λ the Error Correction Term (ECM) coefficient, and $\in_t$ the error term. pq Moreover, denote the optimal lag lengths determined through information criteria like AIC or BIC.

We use a natural logarithmic transformation for all variables, making the coefficients interpretable as elasticities. This reflects the percentage change in CO_2 emissions for a 1% change in each independent variable.

To determine each series' order of integration, unit root testing using Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests is done first. This phase validates the ARDL technique for variables with mixed integration orders (I[0], I[1]).

The ARDL bounds testing procedure ascertains the existence of a long-term equilibrium relationship among the variables. Upon confirmation of co-integration, the model is re-parameterized into an ECM to capture the short-term adjustments and long-term equilibrium dynamics.

The ordinary Least Squares (OLS) technique is used for model estimation, followed by diagnostic tests to confirm the absence of serial correlation, heteroskedasticity, and model stability. This comprehensive approach aims to unravel the complex interplay between economic growth, energy consumption, and environmental impacts, providing insights into the sustainability of current practices.

4. RESULTS

4.2. Unit Root Test

Our econometric research began with Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests to determine variable stationarity. Table 2 shows that LOG (CO_2), LOG (OP), and LOG (AGR) are stationary at levels due to their substantial ADF statistics. Differentiation was needed to obtain stationarity for LOG (GDP), LOG (IND), and LOG (EC), suggesting they are integrated of order one, I(1).

The PP test results in Table 3 corroborate the ADF test findings, with LOG (CO_2) and LOG (OP) being stationary at levels and the remaining variables becoming stationary after differencing. The consistent results from both tests confirm the appropriateness of ARDL bounds testing for co-integration analysis, as the variables are a mix of I(0) and I(1).

The significance of the unit root tests is paramount as they validate the use of the ARDL model for estimating the long-run and short-run dynamics of the variables. The tests indicate a mixture of integration orders within the ARDL approach's methodological framework.

4.2. Lag Selection Criteria

Using the Akaike Information Criterion, the optimal ARDL model lag length was found. Several ARDL model specifications were considered, with the AIC values ranging from −1.90 to −2.02 for the top 20 models (Figure 1). Model3125, with the specification ARDL (4, 0, 0, 0, 0, 0), emerged as the most suitable model based on the lowest AIC value, indicating it provides the best fit with the least complexity among the candidate models. This lag structure implies that the model accounts for four lags of the dependent variable and assumes no lags for the independent variables, thereby focusing on the immediate impact of changes in independent variables on the dependent variable within the selected time frame.

4.3. ARDL Bound Test for Co-Integration

The ARDL Bound Testing approach was employed to examine the existence of a long-term relationship among the variables. The results are presented in Table 4.

The null hypothesis of no co-integration between variables is rejected since the F-statistic of 5.81502 is considerably higher than the upper bound I(1) value of 3.92 at the 5% significance level. With a sample size of 39 and 5 variables (k = 5), the test statistic is far over the critical value constraints, indicating a long-run equilibrium relationship between the series. While variables may diverge in the near term, they tend to move together in the long term, converging towards equilibrium.

4.4. Short- and Long-Run Estimation of Parameters

The short-run parameter estimates, as shown in Table 5, highlight the immediate impact of the independent variables on CO_2 emissions. The lagged values of LOG (CO_2) indicate that past CO_2 levels significantly influence current levels, with the first and third lags being statistically significant. LOG (CO_2[−1]) shows a substantial positive relationship with current CO_2 emissions.

The current period effects of LOG (OP) and LOG (GDP) are positively associated with CO_2 emissions, yielding significant t-statistics. LOG (OP) has a moderately strong effect, while LOG (GDP) presents a more substantial impact. Conversely, LOG (IND)

Table 2: ADF test results

Variable	Level		First difference	
	ADF statistics	Result	ADF statistics	Result
LOG (CO_2)	−3.626**	Stationary	−6.047***	Stationary
LOG (OP)	−4.032**	Stationary	−5.945***	Stationary
LOG (GDP)	−2.723	Non-stationary	−4.885***	Stationary
LOG (IND)	−2.935	Non-stationary	−4.437***	Stationary
LOG (AGR)	−4.889***	Stationary	−2.757	Non-stationary
LOG (EC)	−1.424	Non-stationary	−7.315***	Stationary

*** Highly significant (P<0.01). **Significant (P<0.05). ADF: Augmented Dickey-Fuller

Table 3: PP test results

Variable	Level		First difference	
	PP statistics	Result	PP statistics	Result
LOG (CO_2)	−3.626**	Stationary	−5.969***	Stationary
LOG (OP)	−4.032**	Stationary	−5.945***	Stationary
LOG (GDP)	−2.723	Non-stationary	−4.885***	Stationary
LOG (IND)	−2.935	Non-stationary	−4.437***	Stationary
LOG (AGR)	−4.889***	Stationary	−2.757	Non-stationary
LOG (EC)	−1.424	Non-stationary	−7.315***	Stationary

***Highly significant (P<0.01). **Significant (P<0.05). PP: Phillips-Perron

Figure 1: Akaike information criteria (top 20 models)

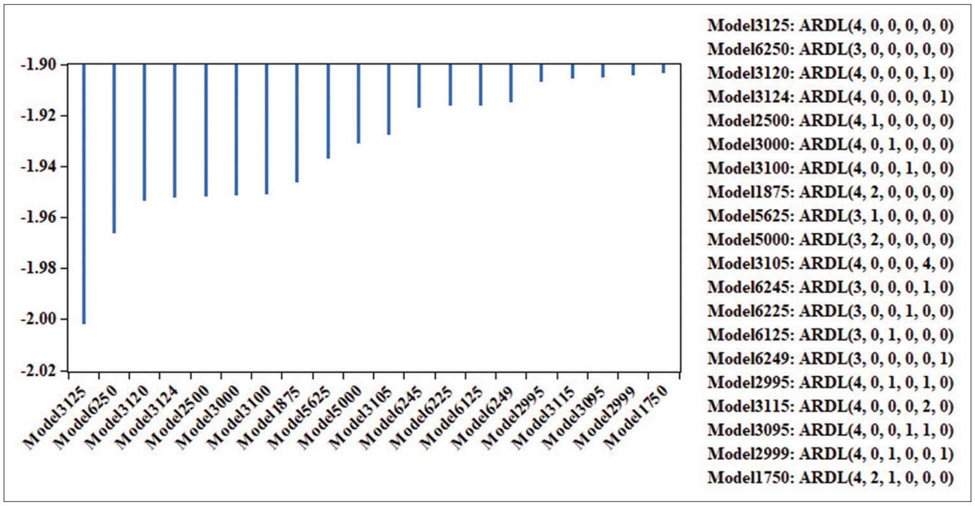


Table 4: ARDL bound test results

F-bounds test	Value	Null hypothesis: No levels of relationship	I (0)	I (1)
Test statistic		Signification (%)		
F-statistic	5.81502	10	2.306	3.353
k	5	5	2.734	3.92
		1	3.657	5.256

ARDL: Autoregressive distributed lag

has a negative effect on CO_2 emissions, suggesting that increases in industrial output may lead to reductions in CO_2 emissions in the short run, a finding that warrants further investigation for potential underlying factors such as efficiency improvements or regulatory changes.

LOG (AGR) and LOG (EC) show an insignificant short-run relationship with CO_2 emissions, indicating that in the immediate term, changes in agriculture, forestry, fishing value-added, and energy consumption do not significantly affect CO_2 emission levels.

The constant term (C) is not statistically significant, indicating that the model does not predict a systematic increase or decrease in CO_2 emissions that is not explained by the model's dynamics.

These results provide insight into the immediate effects of economic activities and energy consumption on environmental quality, which is essential for formulating responsive and timely policy interventions.

The long-run estimation results in Table 6 show that economic variables affect CO_2 emissions. Oil production and GDP increase CO_2 emissions over time, as LOG (OP) and LOG (GDP) are positively and statistically significant. The coefficient sizes indicate a more substantial long-term effect of GDP on CO_2 emissions than oil production.

Conversely, LOG (IND) is negatively associated with CO_2 emissions in the long run, consistent with the short-run estimates. This could reflect structural changes in the industry sector over time, such as advancements in cleaner technologies or shifts towards less carbon-intensive production methods.

Table 5: Short-run estimation results

Variable	Coefficient	SE	t-statistic	Prob
LOG (CO_2[−1])	0.495	0.159	3.107	0.004
LOG (CO_2[−2])	0.182	0.175	1.039	0.307
LOG (CO_2[−3])	−0.389	0.182	−2.133	0.042
LOG (CO_2[−4])	−0.258	0.159	−1.623	0.116
LOG (OP)	0.417	0.155	2.684	0.012
LOG (GDP)	0.855	0.243	3.524	0.001
LOG (IND)	−0.434	0.164	−2.650	0.013
LOG (AGR)	0.027	0.149	0.182	0.857
LOG (EC)	−0.007	0.130	−0.055	0.956
C	3.527	2.139	1.649	0.110

Table 6: Long-run estimation results

Variable	Coefficient	SE	t-statistic	Prob
LOG (OP)	0.430	0.156	2.751	0.010
LOG (GDP)	0.881	0.204	4.327	0.000
LOG (IND)	−0.447	0.151	−2.954	0.006
LOG (AGR)	0.028	0.152	0.184	0.856
LOG (EC)	−0.007	0.134	−0.055	0.956
C	3.636	2.225	1.634	0.113

The variables LOG (AGR) and LOG (EC) remain statistically insignificant in the long run, implying that their contributions to CO_2 emissions are not discernible over the extended period. This suggests that other factors mitigate the impact of agricultural practices and energy consumption on CO_2 emissions in the long run.

The constant term (C) remains non-significant, reinforcing the inference that the model's explanatory variables sufficiently capture the factors influencing CO_2 emissions without needing an additional constant trend.

These findings have profound implications for policymaking, emphasizing the need to consider the long-term environmental consequences of economic expansion and energy use.

4.5. Diagnostic Tests

Several diagnostic tests confirm the model's adequacy, the results of which are compiled in Table 7. The R-squared value of 0.977 indicates that the model explains a high proportion of the variance in the dependent variable. The adjusted R-squared, at 0.970, confirms that the independent variables have a strong explanatory power even after adjusting for the number of variables in the model.

The Durbin-Watson statistic of 2.226 and Breusch-Godfrey Serial Correlation LM test of 0.117 indicate no residual autocorrelation or serial correlation. The Jarque-Bera test shows that residuals have a normal distribution with a P = 0.532. The Breusch-Pagan-Godfrey heteroscedasticity test yields a P = 0.424, indicating consistent residual variance.

These diagnostics indicate that the model does not suffer from common issues such as autocorrelation, non-normality, or heteroscedasticity and can be considered well-specified.

4.6. Stability Check

The model's stability was assessed using CUSUM and CUSUM of Squares tests, as depicted in Figures 2 and 3. The CUSUM test results suggest that the recursive residuals are stable over the sample period, remaining within the critical 5% significance bounds. This indicates that the model's coefficients exhibit no systematic change that would undermine the model's reliability over time.

Similarly, the CUSUM of Squares test displays that the squared recursive residuals are within the 5% significance bounds. This suggests that the variance of the model's errors is stable, reinforcing the model's reliability for forecasting and policy analysis. Both tests indicate that the model's parameters are robust to changes over the time of the study.

Table 7: Diagnostic tests

Test name	Values
R-squared	0.977
adjusted R-squared	0.970
Durbin-Watson statistic	2.226
Jarque-Bera test	1.262 (0.532)
Breusch-Godfrey serial correlation LM test	2.324 (0.117)
Breusch-Pagan-Godfrey test	1.053 (0.424)

Figure 2: CUSUM test graph

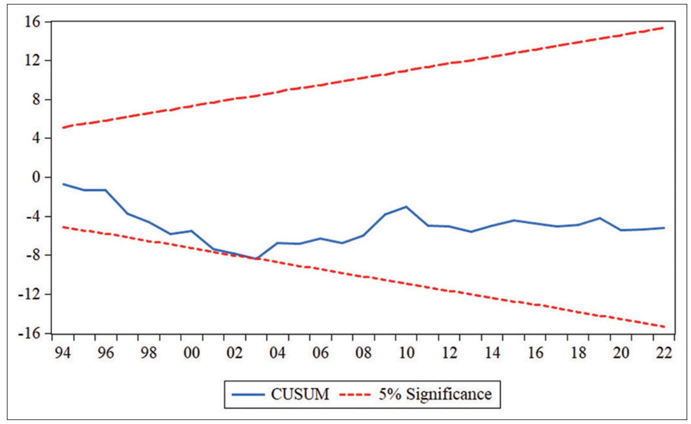
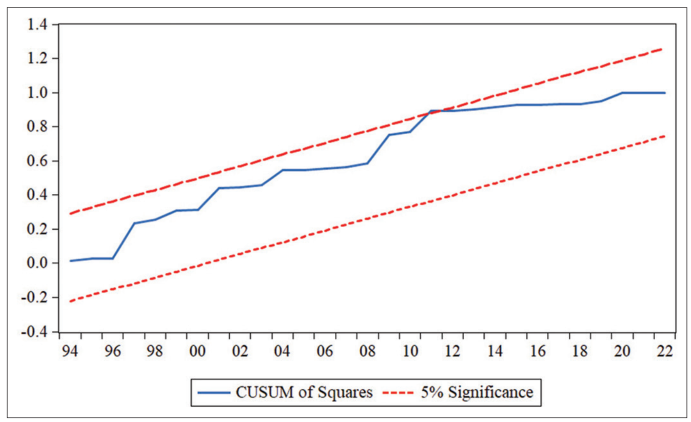


Figure 3: CUSUMSQ test graph



5. DISCUSSION

This empirical analysis reveals the complex connections between economic activities, energy consumption, and carbon dioxide (CO_2) emissions in Saudi Arabia. The findings provide valuable insights that can guide policy decisions in achieving sustainable development and addressing the challenges posed by the relationship between oil and the environment.

The unit root tests have confirmed that the levels of CO_2 emissions (LOG[CO_2]) are stationary, which supports the findings of previous studies conducted by Alshehry and Belloumi (2015) and Alkhathlan and Javid (2015). These studies have emphasized the importance of industrialization and economic growth in causing CO_2 emissions in Saudi Arabia. The transient variations observed in CO_2 emissions highlight the intricacy of Saudi Arabia's emissions factors, mirroring the conclusions of Raggad (2020) and Mahmood et al. (2020) regarding the impact of short-term economic and demographic fluctuations.

Furthermore, the enduring correlation between GDP (LOG[GDP]) and CO_2 emissions is consistent with the existing body of research on the environmental Kuznets curve (EKC) hypothesis. This hypothesis posits that as economies experience initial growth, there is a rise in environmental degradation before it eventually decreases with further development (Van Ruijven and Van Vuuren, 2009). According to Yeh et al. (2010), there is a correlation between economic growth and higher levels of energy consumption and emissions.

The correlation between logarithmic oil production (LOG[OP]) and CO_2 emissions, both in the short and long term, confirms previous studies on the ecological impact of oil production (Brandt et al., 2016; Yusuf et al., 2020). The energy intensity of crude oil production and gas flaring, as measured by LOG (OP), substantially contributes to CO_2 levels (Masnadi and Brandt, 2017), highlighting the crucial need for sustainable practices in the oil industry.

The inverse correlation between industrialization (LOG[IND]) and CO_2 emissions in both the short and long term is remarkable.

This discovery implies that Saudi Arabia is likely experiencing fundamental transformations in its industrial sector, incorporating environmentally friendly technologies or implementing more effective production techniques, as documented in previous research (Orin, 2023).

The findings offer significant contributions to the current body of knowledge by validating and expanding upon specific patterns and connections observed in prior studies. Nevertheless, there are also subtle distinctions and variations that require examination.

The correlation between GDP and CO_2 emissions supports the Environmental Kuznets Curve (EKC) theory. However, the immediate effect of industrialization on emission reduction deviates from conventional predictions in a complex manner. This discovery emphasizes the necessity of additional research on the fundamental elements contributing to this occurrence, such as policy interventions and technological advancements.

Furthermore, the minimal influence of agriculture, forestry, fishing value added (LOG[AGR]), and energy consumption (LOG[EC]) on CO_2 emissions in both the short and long term contradicts the widely accepted notion that these sectors significantly contribute to emissions. This disparity suggests that additional factors, such as technological advancements and measures to improve energy efficiency, are reducing the emissions linked to these industries. This underscores the necessity for further investigation in this field.

This study has significant policy implications for Saudi Arabia's sustainable development goals. The correlation between GDP and CO_2 emissions emphasizes the need to separate economic growth from emissions. Invest in energy efficiency, renewable energy, and sustainable urban planning to reduce energy consumption and emissions. The oil industry must consider environmental issues due to the long-term positive relationship between oil production and emissions. Implementing CCS and switching to cleaner energy sources can reduce oil production's environmental impact. The counterintuitive inverse correlation between industrialization and emissions in the short and long term suggests that Saudi Arabia may be adopting greener industrial methods. Policymakers should support these positive developments while ensuring long-term viability and environmental compliance.

This empirical analysis improves our understanding of oil and the environment in Saudi Arabia and informs policy decisions. The complex relationships between economic activities, energy use, and CO_2 emissions highlight the need for a holistic approach to sustainable development in the nation.

6. CONCLUSION

This study examines the complex relationship between economic factors and carbon dioxide (CO_2) emissions in Saudi Arabia, focusing on total primary energy consumption, oil production, agriculture, GDP, and industry value added. The study examines CO_2 emission drivers, environmental policies, and ways to reduce carbon emissions while achieving sustainable economic growth. The study also examines the effects of Saudi Arabia's Vision 2030 initiative on CO_2 emissions and sustainable development. This study examines the complex relationships between economic factors, energy consumption, and CO_2 emissions in Saudi Arabia, providing valuable empirical insights for this oil-rich nation. It also evaluates the ability of Saudi Arabia's Vision 2030 sustainability initiatives to reduce CO_2 emissions and boost economic diversification, providing policymakers with a comprehensive benchmark.

The study highlights CO_2 emissions drivers and their interaction with economic activities, emphasizes renewable energy investments, and advocates for a balanced oil production approach to inform policy decisions. These insights inform policies on economic diversification, renewable energy adoption, and environmental sustainability, helping Saudi Arabia achieve its Vision 2030 goals.

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