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# Analyze the impact of energy consumption, economic development, trade liberalization, and urbanization on CO2 emissions in Saudi Arabia

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**A B S T R A C T**

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The increasing worldwide focus on sustainable development has drawn significant attention to environmental issues. The focus is on minimizing energy usage to lessen environmental harm. However, conversations regarding this subject have raised worries. Sustainable development is gaining respect from economists and policymakers due to its potential impact on productivity. The reason for conducting this research is to evaluate the effects of energy consumption, economic growth, trade liberalization, and urbanization on carbon emissions within the context of Saudi Arabia. The data was collected longitudinally from 1980 to 2022 and comes from World Development Indicators and Our World in Data. The study found cointegration among the variables using the ARDL model Short-term CO2 emissions were inversely related to previous delays, economic growth, and trade liberalization, but directly connected to energy consumption and urbanization. Long-term data demonstrates that the usage of energy, urbanization, and trade liberalization have a positive correlation with CO2 emissions, but economic development and previous CO2 emissions have a negative correlation. The study's results are briefly discussed, and several recommendations are made accordingly.



## 1. Introduction

Climate change stands as one of the most pressing environmental challenges confronting humanities today. The increasing amount of carbon dioxide (CO2), the main cause of the impact of global warming, seems to make the scenario worse. The impact of global warming primarily stems from the emissions of Global warming gases (GHGs) caused by human activities. As per Our World in Data, the fossil fuels and industry were responsible for approximately 35 billion tons in 2022 (Our world in data 2024). Emissions growth has decelerated in recent years, but they have not yet reached their highest point, as depicted in Fig. 1 below. According to the data shown in Fig. 1, there has been a notable rise in CO2 emissions levels over the years. Specifically, the amount of carbon dioxide that is released into the atmosphere on an annual basis has climbed from 5 billion tons per year in the middle of the 20th century to 35 billion tons. Furthermore, the atmospheric concentration of carbon dioxide has risen from 280 parts per million (PPM) in 1750 to 420 PPM in 2021, marking a 50% growth over the mentioned period. The main driver behind this increase in CO2 emissions and intensification is attributed to revolution in the industrial sector (Ardakani & Seyedaliakbar, 2019). The industrial revolution brought about a substantial shift in the manner that society carried out its functions, leading to substantial socioeconomic changes known as urbanization and industrialization in various countries (Cai et al., 2018). Considering the beginning of the industrial revolution in the Western world, the idea that there is a relationship between urbanization and industrialization has gained widespread acceptance around the world (Chandran & Tang, 2013). The obvious objective of economies is to attain greater economic growth and prosperity, which is the basis for this association (Cai et al., 2018). While this mutual relationship has proven beneficial by expanding production capacity and hence contributing to the expansion of the economy in both developed and developing nations, it has also contributed to climate changes. Urbanization and industrialization have led to modernization and better living conditions but have also introduced notable health issues that must be acknowledged (Shaari et al., 2022).

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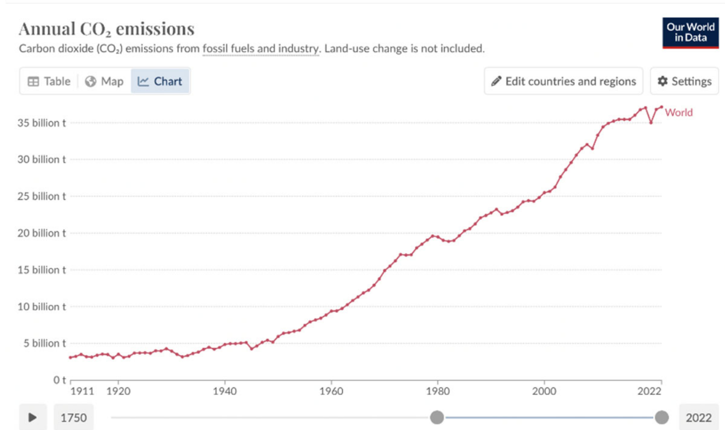


**Fig. 1.** Carbon dioxide concentrations in the atmosphere and annual emissions have been measured.

The rising living standards have driven an increased demand for foreign goods, stimulating the growth of commerce and the movement of products across countries. This has required a substantial quantity of energy consumption, ultimately leading to a surge in energy demand and subsequent CO2 emissions (Mahmood et al., 2020).

Our study aims to address this gap in knowledge by using both environmental and growth functions to demonstrate the effectiveness of trade liberalization, urbanization, and energy consumption on CO2, in the Saudi Arabian economy. To our knowledge, no prior studies have explored this topic. Moreover, our study adds value to the field by examining the causal linkage between economic growth, trade liberalization, urbanization, energy consumption, and carbon emissions in both short-term & long-term perspectives, employing the ARDL technique. Those remaining in the article is arranged in such a way outlined below: Section 2 examines the current literature; In the third section, the data and the econometric model are discussed.; Section 4 explains the empirical technique applied; On the other hand, Section 5 presents and analyzes the findings, in addition, the research is ended in Section 6.

## 2. Literature review

In this section, we explore what is the connection between rising economic activity and rising energy consumption, urbanization, and trade liberalization in a previous literature review. Saboori et al. (2012) looked at the dynamics of the link between gross domestic product (GDP) and CO2 emissions in Malaysia from 1980 to 2009. The Environmental Kuznets Curve (EKC) hypothesis was shown to be present in Malaysia, as demonstrated by their research, which utilized the ARDL approach. The results of the VECM indicated that there is a non -directional connection between pollution and economic growth. Öztürk and Al-Mulali (2015) investigated the relationship between Tunisia's GDP, foreign direct investment (FDI), urbanization, and environmental issues from 1971 to 2012. The findings of the ARDL indicated that real GDP appears to have a beneficial impact on CO2 emissions.

Öztürk and Al-Mulali (2015) studied the effects of the influence of GDP and FDI on pollution in Caribbean Countries and Latin America from 1980 to 2010 and suggested that FDI exacerbates pollution levels. The study conducted by Muhammad (2019) examined pollution dynamics in Cambodia from 1996 to 2018. Findings from the generalized method of moments (GMM) and two-stage least squares (2SLS) analyses indicated that both GDP and energy consumption contribute to pollution. Çetin et al. (2015) examined the connection between urbanization and carbon dioxide emissions in economies located in sub-Saharan Africa between the years 1985 and 2010. Using the vector error correction model (VECM) methodology, the research demonstrated that there is a causal relationship between the variables that were being investigated in both directions.

Aye and Edoja (2017) investigated the impact that pollution has on the expansion of the economy (EG) via the (GMM) technique. The study found that in 31 developing countries, low economic growth is linked to reduced CO2 pollution, while high economic growth is connected to higher CO2 emissions, contradicting the EKC hypothesis. The study suggests transitioning to low-carbon technologies to promote sustainable economic growth. Dogan et al. (2017) studied the factors that contributed to pollution in 27 economies that were members of the OECD from 1995 to 2010. Using the LM bootstrap panel co-integration test, they were able to establish that the variables were significantly correlated with one another. When it came to environmental quality in OECD nations, the results of the DOLS approach suggested a positive link with GDP, although GDP squared, and tourism had negative effects on the quality of the environment. From 1970 to 2013, the link between energy consumption, economic growth, and carbon dioxide emissions in India was the subject of an inquiry that was carried out, the VECM was utilized to analyze the connection between the individual series (Ohlan, 2015). All the factors that are used to explain CO2 emissions were shown to have a positive impact, according to the ARDL model. According to the findings, India should prioritize the use of renewable energy sources, maintain energy consumption levels, provide subsidies to renewable energy sources, and impose taxes on the consumption of non-renewable energy sources to improve the overall ambiance of the place.

An investigation of the connection between urbanization and pollution was carried out utilizing data from Singapore spanning the years 1970 to 2015 by Ali et al. (2017). For gaining the benefits of co-integration analysis, they utilized the ARDL approach, which led them to discover that urbanization had a negative influence on pollution. Hanif (2018) performed an analysis using panel data gathered from 34 developing economies in Sub-Saharan Africa from 1995 and 2015. GMM studies suggested that fossil fuels, solid fuels, and fast urbanization all contribute to environmental deterioration. These conclusions were derived from an investigation of the empirical impacts of urban growth, fossil fuels, and solid fuels on environmental degradation. Mikayilov et al. (2018) investigated the connection between the state of the economy and the level of pollution in Azerbaijan between the years 1992 and 2013. A substantial long-run association was shown to exist across the sample period when Johansen, ARDLBT, FMOLS, DOLS, and CCR analyses were utilized. The findings of these analyses were consistent across all methodologies (Taher, 2020), the OLS method was utilized to analyze the data from Lebanon spanning the years 1988 to 2018, with the purpose of determining the influence that economic development and FDI have had on the environment. Using the least absolute deviation (LAD), the research concluded that FDI and economic expansion both result in higher CO2 emissions. Afridi et al. (2019) performed a survey during the years 1980 and 2016, the EKC hypothesis was evaluated in eight different SAARC nations. Through the utilization of the squared term for GDP, they discovered data that substantiates the existence of an inverse U-shaped link between GDP and pollution in particular nations.

From 1983 to 2013, an investigation was conducted in South Asia to study the link between energy consumption, urbanization, and the environment (Siddique et al., 2016). When Granger causality tests and panel co- integration analysis were used to investigate long-term connections, the researchers concluded that both energy use and urbanization had a detrimental effect on the quality of the environment. Experiments have shown that there is a causal relationship between CO2 emissions and both energy use and urbanization. This relationship is bidirectional.

In Sarvari (2019), climate change and the relationship between urbanization and these two factors was investigated throughout seven different areas of Iran over the course of five-time frames running from 1976 to 2016. In the study, the Pearson test was utilized inside SPSS to determine the degree of correlation that existed between these variables. According to the findings of the empirical research, urbanization has a gradually negative impact on the average temperature and precipitation levels in the areas of Iran. Salahuddin et al. (2019) analyzed the influence of urbanization on pollution by using data from 44 Sub-Saharan African economies between 1984 and 2016. The study utilized advanced second-generation methodologies to determine that urban population expansion has a substantial impact on CO2 emissions. The report suggests that the SSA areas should establish strong governance and energy policies to reduce environmental deterioration. Shaari et al. (2022) did an investigation during the years 1978 and 2013 to determine the impact that economic considerations had on environmental pollution in Malaysia. As factors that functioned as explanations, economic indices such as GDP, FDI, energy consumption, urbanization, and trade were utilized. Both the Engle-Granger causality tests and the ARDL model demonstrated that there is a direct connection between environmental contamination and economic indices. A U-shaped link between FDI and ecological deterioration in Malaysia was, according to the findings of the study validated.

In (Gasimli et al., 2019), the bound test of co-integration was utilized to investigate the influence that urbanization and energy consumption had on pollution levels in Sri Lanka between the years 1978 and 2014. This investigation was driven by the persistent rise in carbon dioxide emissions that have been seen in Sri Lanka. To account for unidentified structural changes or breakage, the Zivot-Andrew (ZA) unit root test was taken into consideration. Based on the data, it was determined that the use of energy and the urbanization of areas both contribute to the rise in pollution levels. In (Mahmood et al., 2020) during the years 1968 and 2019, an investigation was conducted in Saudi Arabia to study the relationship between industry, urbanization, and pollution. The preponderance of oil-exporting nations and the expansion of the industrial sector, which supports fast urbanization, are the two primary factors that are driving the investigation of these links. Based on the results that were got from the ARDL methodology, one might reach the conclusion that the explanatory factors have a more significant and favorable influence on pollution in linear models as opposed to non-linear studies. By utilizing the ARDL model, Ali et al. (2016) investigated the environmental effects that were brought about by the expansion of the economy and the use of energy in Nigeria from 1971 to 2011. Based on their findings, it appears that urbanization does not have a substantial impact on CO2 emissions in Nigeria. On the other hand, economic expansion and energy use are strongly connected with pollution. In (Anwar et al., 2020), a panel of countries from Far East Asia was used to explore the factors that determined pollution from 1982 to 2017. The Fixed Effect Model was used for this investigation. According to their empirical findings, economic development and fast urbanization are two of the most important factors that contribute to pollution. This is even though CO2 emissions are continually increasing, which poses serious problems for both human health and the environment.

Another study was performed from 1991 to 2016 to evaluate the link between urbanization, The functioning of institutions and the condition of the environment in certain nations that are members of the Organization of Islamic Cooperation (OIC). The Dynamic Common Correlated Effects (DCCE) model was utilized to investigate the connections between these factors. The ecological footprint, which was quantified in global hectares using the gha unit of measurement, was used as the instrument for establishing the level of environmental quality being investigated in the research. According to the findings, urbanization comes with an increase in the ecological imprint that one leaves behind, but institutional performance has a negative impact on being left behind. According to the findings of the study, the Organization of Islamic Cooperation (OIC) should prioritize the improvement of institutional frameworks to enhance environmental quality. In (Li et al., 2018), the study was conducted in China between the years 2000 and 2010 to evaluate the relationship between urban population and CO2 efficiency. Specifically, the focus was on CO2 efficiency, which may be defined as the ratio of goal CO2 emissions to actual emissions. To determine the effectiveness of controlling carbon dioxide emissions, an application of data envelopment analysis as well as window analysis was made. According to the findings of the Spatial Lag Panel Tobit model, Urbanization was the primary driver of CO2 emissions. According to the findings of the study, cities should consider transferring low-carbon technology to their neighboring metropolitan regions. In (Khan et al., 2020) from 1965 to 2015, an empirical investigation was conducted to explore the link between the expansion of the economy and the consumption of energy sources that are not renewable in Pakistan. According to the findings of the ARDL model, both energy use and emissions of greenhouse gases are factors that lead to elevated levels of pollution.

Muhammad et al. (2020) conducted empirical estimation across 65 Belt and Road Initiative economies from 2001 to 2016. They employed quantile regression to analyze the impact of urbanization on pollution. Due to concerns regarding endogeneity, the Two-Stage Least Squares (2SLS) model was utilized. Findings supported an inverse U-shaped Connection between urbanization and pollution. In research that was conducted not too long ago (Alfantookh et al., 2023) the authors investigated the implications of transitioning towards manufacturing on the environment in the context of Saudi Arabia's Vision 2030 during the period of 1971-2021. There is no evidence to support the validity of the inverted U-shaped Kuznets function anywhere in Saudi Arabia during the period that the study was carried out, according to the findings of the study.

## 3. Methodology of the research

### *3.1 Data*

Fig. 2 illustrates the procedure that was utilized in the study approach. The sample period encompasses the years 1980 through 2022. Every single piece of information that was used for the variables in this study was secondary data that was obtained according to the “World Development Indicators (WDI) database” maintained by the World Bank. Additionally, the statistics per year yearbook of the Kingdom of Saudi Arabia reports on a variety of years. Table 1 provides a description of the factors that were discussed.

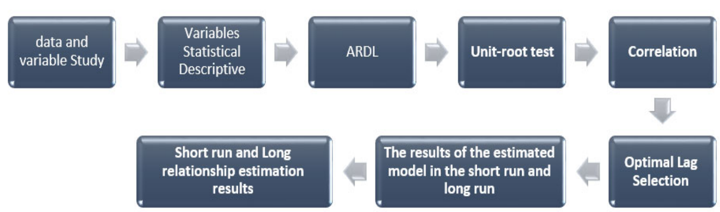


**Fig. 2.** Steps of Applied Study

**Table 1**
An explanation of the factors that are being considered.

| Factors | Notation | Unit |
|---|---|---|
| CO2 emissions | *CO2* | Metric tons per capita |
| Per capita energy consumption | *EC* | kWh |
| Economics growth | *Y* | Constant 2018 USD |
| Trade liberalization | *TO* | %of GDP |
| Total urban population | *UB* | |

In Table 2, we provide a statistical summary for the variables. To assess the similarity of values among certain variables (LCO2, LEC, LY, LTO and LUB), we applied a logarithmic transformation. The remaining variables were calculated using percentages or per capita measures (Gujarati & Porter, 2009). The standard deviations of all variables are close to zero, indicating that the data points are closely grouped around the averages.

**Table 2**
Statistical description of variables.

| | $LCO_2$ | LEC | LY | LTO | LUB |
|---|---|---|---|---|---|
| **Mean** | 5.382 | 6.239 | 9.547 | 9.325 | 4.1082 |
| **Median** | 5.540 | 6.471 | 9.720 | 9.443 | 4.4961 |
| **Maximum** | 5.878 | 6.970 | 11.346 | 10.67 | 4.8321 |
| **Minimum** | 4.344 | 3.192 | 8.292 | 6.142 | 4.095 |
| **Std. Dev.** | 0.671 | 0.942 | 0.279 | 0.312 | 0.2321 |
| **Observations** | 42 | 42 | 42 | 42 | 42 |

### *3.2. Econometric Model*

Through the utilization of the ARDL model (NKoro et al., 2016), the econometric technique was applied in the study to test hypotheses. This model is a relatively new dynamic technique that considers the factor of time to determine those interactions between variables that are both short-term & long-term. The relationship between CO2 emissions, energy consumption in the trade liberalization, economic growth, and urban population expansion is outlined by Eq. (1), which provides an idea of how this link might be established.

$$CO_2 = \alpha + \beta_1 EC + \beta_2 Y + \beta_3 TO + \beta_4 UB + \mu_t \quad (1)$$

During the process of analyzing time-series data, it is recommended to convert Eq. (1), into logarithms. This conversion helps in examining the percentage in environmental degradation that occurs due to a percentage change in energy consumption. Additionally, a national logarithmic transformation is conducted to tackle any potential non -linear relationships between which variables are dependent and which are independent. As a result, the new equation can be expressed as follows:

$$\mathrm{LNCO_2} = \alpha + \mathrm{Ln}\beta_1\mathrm{EC} + \mathrm{Ln}\beta_2\mathrm{Y} + \mathrm{Ln}\beta_3\mathrm{TO} + \mathrm{Ln}\beta_4\mathrm{UB} + \mu_t \quad (2)$$

LNCO2 represents the logarithm of CO2 emissions, LNEC indicates that the logarithm of per capita energy consumption, LNY indicates that the logarithm of income, LNTO represents the logarithm of trade liberalization, and LNUB represents the logarithm of urban population. The study employed the ARDL model in the research, known for its dynamic nature and consideration of time. To do this, it was necessary to conduct research on the short-term and long-term links that exist between the variables as well, and to ascertain the rate at which the system approaches equilibrium. With the use of time series data, the study carried out an investigation into the long-term connections that exist between the variables. For the ARDL model, there are two different components. The first component is the autoregressive (AR) component, which incorporates the dependent variable as a lagged independent variable and relies on the values of the dependent variable that have been lag-timed. The second component is the distributed lagged (DL) component, which gives the impression that the dependent variable is affected by shifts in the values of the independent variables and the lagged values of those variables.

$$\begin{aligned} \mathrm{dLnCO2}_{2t} = {} & \alpha_0 + \alpha_1 \mathrm{LnCO}_{2t-1} + \alpha_2 \mathrm{Ln}EC_{t-1} + \alpha_3 \mathrm{LnY}_{t-1} + \alpha_4 \mathrm{LnTO}_{t-1} + \alpha_5 \mathrm{Ln}UB_{t-1} \\ & + + \sum_{j=1}^{p} \beta_{1j}\Delta \mathrm{LCO_2}_{t-j} + \sum_{j=0}^{q} \beta_{2j}\Delta \mathrm{LEC}_{t-j} + \sum_{j=0}^{n} \beta_{3j}\Delta \mathrm{Ln}Y_{t-j} + \sum_{j=0}^{r} \beta_{4j}\Delta InTO_{t-j} \\ & + \sum_{j=0}^{m} \beta_{5j}\Delta \mathrm{Ln}UB_{t-j} + \mu_{it} \end{aligned} \quad (3)$$

In Eq. (3), the symbol (d/) represents the initial derivative operator *p, q, r, n*, and *m* represent lags, $\alpha_1$ to $\alpha_5$ represent long-term variables, $\beta_1$ to $\beta_5$ represent short-term variables, $\alpha_0$ represents the interception, and $\mu$ represents the error term.

## 4. Findings

In this study, we have used secondary data on macroeconomic variables for our analysis. It is vital to evaluate the stability of the data, so we have conducted an analysis to determine the presence of a unit root. We have employed the Augmented Dickey-Fuller (ADF) approach, known for its effectiveness in previous research studies. Economic analysis methods have been commonly employed to examine periodic fluctuations in the average and variability of time-series data. The unit root test allows us to evaluate the null hypothesis, suggesting non-stationarity in the data, against the alternative hypothesis, which implies data stationary. Table 3 contains the findings that were obtained from the unit root test that was carried out using the ADF technique, evaluating the stability of all variables. Upon accounting for the intercept and absence of trend, the analysis indicates that *LnEC, LnY, LnTO*, and *LnUB* possess unit roots, suggesting they are not stationary at the current level. Upon applying differencing once, all variables stabilize. However, when considering an intercept and trend, the findings reveal that only *LnY* and *LnTO* exhibit unit roots, indicating they are not stationary initially. Conversely, *LnCO2, LnEC, LnY, LnTO*, and *LnUB* demonstrate stationarity at the initial level as they lack unit roots. Nonetheless, all variables achieve stationarity through differencing. In summary, the variables in this study display varying degrees of integration, with some being integrated of order 1 (I(1)), while others are integrated of order 0 (I(0)), indicating applicability of the ARDL technique.

**Table 3**

Augmented Dickey-Fuller Test

| Factors | Intercept | | Intercept with trend | |
|---|---|---|---|---|
| | Level | First difference | Level | First difference |
| $LnCO_2$ | −5.3804*** | −5.4300*** | 0.2344 | 0.0000 *** |
| LnEC | −2.0449 | −4.6965*** | 0.4258 | 0.0002 *** |
| LnY | −1.0627 | −1.4204*** | 0.5635 | 0.0001 *** |
| LnTO | −0.1733 | −2.3548*** | 0.7589 | 0.0011 *** |
| LnUB | −2.1287** | −0.4083** | 0.8986 | 0.0000 *** |

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

**Table 4**

Bounds test result

| F-statistic | | 6.2355*** |
|---|---|---|
| Critical value | Lower bound | Upper bound |
| 10% | 1.55 | 2.79 |
| 5% | 2.17 | 3.06 |
| 1% | 2.91 | 3.67 |

Note: *** denotes significance at 1%.

We conducted the ARDL bounds testing technique, and the outcomes are displayed in Table 4. The F- statistic of 6.2355 exceeds the critical value of 3.67, indicating the rejection of the null hypothesis of no cointegration. This discovery implies that we can move forward with estimating the long-run and short-run effects. Furthermore, we utilized the Akaike Information Criterion (AIC) to automatically choose the optimal lag for our analysis.

**Table 5**

Short-term estimation results

| Factors | Coefficient | Std. Error | T-Statistic | Prob |
|---|---|---|---|---|
| LnEC | -0.0515* | 0.0066* | -1.0866** | 0.0028 |
| LnY | 0.22116 | 0.0231 | 3.2532 | 0.0040 |
| LnTO | -0.0208 | 0.0691 | -2.3473* | 0.0860 |
| LnUB | 0.2005* | 0.0219* | 1.0338 | 0.0091 |
| C | -2. 5158** | 0.0602** | -4.7606** | 0.0000 |
| ECT | -0.3479*** | 0.0398*** | -5.0843*** | 0.0000 |

Notes: *** , ** and * indicate significance at the 1% , 5% and 10% levels, respectively.

*4.1 Short term estimation results*

The findings from both Table 5 and Table 6 provide insights into the short-run and long-run relationships. Table 5 reveals that *LnEC, LnY, LnTO*, and *LnUB* significantly influence CO2 levels in Saudi Arabia in the short term. Additionally, the outcomes of the error correction have been shown in Table 6, which demonstrates that the error correction term has a high significance level at a significance level of 5%, with a negative sign that was predicted. A score of 2.5 indicates that there is a short-term connection that is in balance or cointegration between the factors in the model, which provides support for the existence of such a link. Consequently, within one year, the system corrects deviations from the equilibrium, moving back towards the short-term equilibrium. Notably, the coefficient for *ECT* is -0.3479, signifying its significance and confirming the presence of short-run relationships between energy consumption, trade op, economic growth, population growth, and CO2 emissions.

*4.2 Long term estimation results*

According to the estimations for the long term, there is a statistically significant correlation and robust economic relationship between the levels of carbon dioxide and the amount of energy that is used, which indicates that the relationship is advantageous over the long term. Specifically, with each one-unit increase in energy consumption, CO2 levels rise by 0.4767 units. Similarly, for every one- unit decrease in trade liberalization, CO2 levels increase by 0.2795 units, and for each one-unit decrease in urbanization, CO2 levels increase by 0.1872 units.

**Table 6**

Long term estimation results

| Factors | Coefficient | Std. Error | T-Statistic | Prob |
|---|---|---|---|---|
| LnEC | 0.5346 | 0.029837 | -34.67733 | 0.0000 |
| LnY | 0.4767 | 0.090698 | 27.30756 | 0.0000 |
| LnTO | -0.2795 | 0.016479 | 35.16976 | 0.0000 |
| LnUB | -0.1872 | 0.009204 | 27.73612 | 0.0000 |
| C | -0.002504 | 0.000760 | -3.296092 | 0.0017 |

Notes: *** , ** and * indicate significance at the 1% , 5% and 10% levels, respectively.

Clearly, as can be shown in Table 7, the results of the diagnostic tests comprised a variety of evaluations. These evaluations included the Jarque-Bera test, the Breusch-Godfrey series correlation test, the heteroskedasticity test, and Ramsey's stability test. All these tests concluded that the F-statistics did not meet the criteria for statistical significance (Gujarati & Porter, 2009). However, these findings suggest that the utilized model does not exhibit any diagnostic issues. Additionally, the variables under examination in this study, namely energy consumption, trade liberalization, economic growth, and urbanization, do not demonstrate any diagnostic problems, as illustrated in Table 7.

**Table 7**
Diagnostic Tests Results

| F-Statistic = 5.9146 | | |
|---|---|---|
| **Statistical Tests** | **F-Statistics** | **Probability** |
| Jarque-Bera | 0.079 | 0.673 |
| Breush Godfrey collecting series | 0.165 | 0.795 |
| Heteroskedastisity test | 1.781 | 0.102 |
| Reset Ramsey Stability | 1.435 | 0.1687 |

We utilized Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMSQ) charting to validate the model's stability (please refer to Fig. 3 below for further explanation). The stability of the model that was used is demonstrated by the fact that all the points that were plotted are contained within the red boundaries, as seen in both graphs.

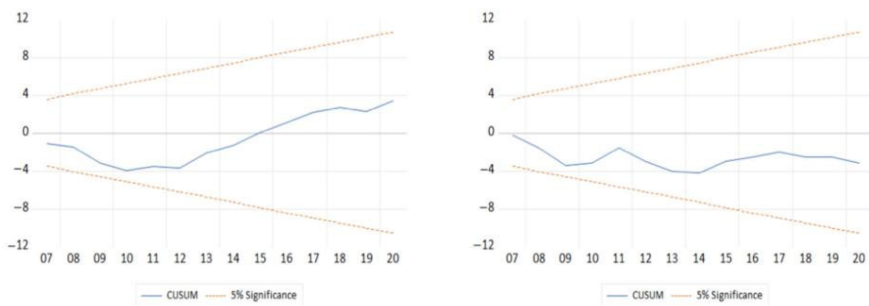


**Fig. 3.** CUSUM and CUSUMQ

## 5. Discussion

The findings reveal that economic development energy use has a harmful effect. influence on $CO_2$ emissions, but urbanization and trade liberalization have considerable beneficial benefits, as evidenced by the long-run coefficients. This is the case given that the results are presented. There exists a connection between the rapid expansion of the economy and a decrease in $CO_2$ emissions over the long term. According to the long-run positive coefficient of energy usage, there is a correlation between growing energy consumption and increased pollution. This fact suggests that energy consumption is the key factor that contributes to the production of carbon dioxide in Saudi Arabia. The results are consistent with the findings (Ali et al., 2016a, 2016b, 2017, 2020, 2021). The argument that trades boosts economic growth, which in turn increases $CO_2$ emissions, is supported by the fact that the long-run coefficient of trade liberalization turns out to be positive. Research that was done in the past that linked globalization and commerce to $CO_2$ emissions is consistent with this finding. On the other hand, trade may also play a part in lowering $CO_2$ emissions by encouraging the development of energy-efficient technology and the use of manufacturing methods that are less polluting. As a result of trade, the dissemination of innovative technology and practices that contribute to the reduction of $CO_2$ emissions can be facilitated. It is possible to achieve long -term reductions in utilization of non-renewable energy sources and $CO_2$ emissions by promoting the use of renewable energy sources and putting into action programs that save energy. The negative effects that urbanization has on the environment may be mitigated by the implementation of sustainable urbanization initiatives. Some examples of these techniques include promoting green cities and improvement of transportation infrastructure. According to the EKC hypothesis, which is supported by these data, initial economic development may result in increased environmental degradation; however, destruction of the environment reduces as nations progress and adopt technology that are less harmful to the environment. The findings of this study highlight how important it is for Saudi Arabia's officials to make the deployment of methods that are environmentally friendly a top priority to lessen the amount of carbon dioxide emissions.

Important strategies include encouraging the use of renewable energy sources, promoting sustainable urbanization, and investing in environmentally friendly technology. Several policy proposals may be created to reduce $CO_2$ emissions in Saudi Arabia, and these recommendations can be derived from the findings presented here. In the first place, it is essential to increase the usage of renewable energy sources and to push for energy conservation techniques to reduce the amount of energy that is consumed.

Second, to lessen the amount of carbon dioxide emissions, government officials ought to provide financial incentives for investments in environmentally friendly technologies, notably within the industrial sector. The third point is that the economic framework of Saudi Arabia ought to give priority to sustainable urbanization by enacting policies that encourage the development of green cities and transportation infrastructure. For this reason, it is of the utmost importance to increase regulatory control in the commercial sector to guarantee that enterprises operate in a manner that is ecologically friendly. By reducing carbon dioxide emissions and promoting sustainable behaviors, we can not only facilitate the development of a world that is healthier and more robust, but we can also open new economic opportunities and cultivate a society that is more equitable and affluent.

## 6. Conclusion

Through the utilization of temporal data extending from 1980 to 2022, the reason for doing this study was to conduct an empirical investigation into the short term and long-term causal connections that exist among carbon dioxide emissions, energy consumption, economic development, trade liberalization, and urbanization for the Kingdom of Saudi Arabia. In this work, the ARDL model was applied. The random forest model consists of an ensemble of several decision trees, each of which provides a forecast on its own. These predictions are then aggregated to form an overall prediction. The results of the ARDL model indicate that over the course of a long period of time, energy consumption, urbanization, and trade liberalization have a positive influence on carbon emissions, but earlier carbon emissions and economic development have a negative effect. Short-term relationships demonstrate a negative link between past carbon emissions, economic development, and trade liberalization with carbon emissions, whereas energy consumption and urbanization exhibit a positive connection. The adoption of renewable energy can help Saudi Arabia transition away from reliance on fossil fuels, leading to reduced air pollution and opening more job opportunities. Furthermore, the development of new mass transit systems and the expansion of current ones can help reduce vehicle emissions and generate new employment opportunities. Going forward, this will also stimulate economic growth by capitalizing on agglomeration economies. The preservation and improvement of wetlands and forests will enhance agricultural output, mitigate $CO_2$ emissions, and bolster resilience against environmental stressors.

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