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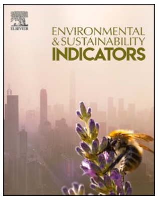

# An environmental impact assessment of Saudi Arabia's vision 2030 for sustainable urban development: A policy perspective on greenhouse gas emissions

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ABSTRACT

Globally, countries are legitimizing actions to curtail the malevolent impacts of environmental degradation. This study examined the interaction between $CO_2$ emissions and selected economic variables within the framework of Saudi Arabia's Vision 2030. The Autoregressive distributed lag model (ARDL) was used to analyze the long-run relationships and short-run dynamics between studied variables (1970–2020). The Mann-Kendall (MK) test revealed a significant ($p < 0.05$) positive increase of GHGs emissions from all sectors across the KSA. The highest increased were captured at the electricity and heat by 7345454.47 tonnes of carbon dioxide-equivalents/year ($p < 0.05$). On the hand, the ARDL model indicates that GDP, agriculture, industry, services, and oil production have short-term effects on the environment through $CO_2$ emissions. Therefore, GDP, agriculture, services and oil production contribute to increases in $CO_2$ emissions. While industry contributes to decrease in $CO_2$ emissions. The ARDL model also showed that an increase in GDP of 1 percent increases $CO_2$ emissions by 3.46 percent, while an increase in oil production of 1 percent increases $CO_2$ emissions by 4.04 percent. However, an increase in industry of 1 percent decreases $CO_2$ emissions by 7.25 percent. The output of this research has a policy implication for addressing environmental concerns in the country.

## 1. Introduction

Global climate change triggered by increasing greenhouse gases (GHGs) emissions, mainly $CO_2$, poses a distinctive threat to the environment, development, and sustainability (Raihan, 2023a). The concentration of pollutant emissions will rise because of rising $CO_2$ emissions as well as population and GDP growth (Ata et al., 2022). Therefore, improvement of the quality of environmental by decreasing emissions remains the fundamental pillar in contributing to the achievement of sustainable development goals (Raihan et al., 2022). Moreover, economic growth policies that are sustainable are anticipated to abate global warming and stimulate environmental sustainability (Torun et al., 2022) as prescribed in the Paris Agreement (UNFCCC, 2015). The Kingdom of Saudi Arabia is listed among the top twenty economies due to its to enormous oil reserves and swift economic transition raised per capita income (Alkhathlan and Javid 2015; Qiao et al., 2019). The gross domestic product has been increasing for example by 29% in 2000, 79.7% in 2010, and 129.7% percent (worldbank, 2015). However, Saudi Arabia is generally more susceptible to climate change than other countries. The country's makeup and the sensitivity of its resources are to blame for this.

The petroleum industry, petrochemical industry, and fossil fuel exports are Saudi Arabia's primary sources of income. There are also a limited number of sustainable water sources described in vision 2030

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(Economy and Business - Vision, 2030; 2023). According to the Saudi central bank, "Public Finance" states that between 50.29 and 59.84 percent of the total earnings for the general budget of the state were generated by the oil industry in Saudi Arabia between 2017 and 2020 (central bank, 2023). Saudi Arabia exclusive reliance on oil and natural gas as the major source of energy and revenue implies it produces enormous $CO_2$ emissions hence contributing global climate change crisis (Alshehry and Belloumi, 2015; Therefore, Saudi Vision 2030 was designed with specific interest to balance and achieve environmental, economic, and social goals (Alajlan and Alreshaidi, 2023). Being the key member of OPEC, the Kingdom is dedicated to the organization's overarching environmental conservation policy, which acknowledges the need to abate emissions, as was confirmed at the Twenty-sixth Conference of the Parties in Glasgow, United Kingdom. This includes ensuring that energy is available and accessible for everyone, following Goal 7 of the Sustainable Development Goals (OPEC Annual Statistical Bulletin, 2022).

Saudi Vision 2030, which covers all facets of life, was introduced in 2016 by the Kingdom. The aim is to endeavor to save the environment and revive environmentally sustainable practices. The implementation of integrated waste management and waste recycling projects in the Saudi capital city, the launch of national renewable energy programs and the preparation of wind energy facilities, the establishment of national recycling investment companies, the establishment of reserves, the Kingdom's official membership in the International Solar Energy Alliance, and the adoption of the circular carbon economy initiative Join the Global Methane Pledge, create an Energy and Environment Research Fund, and aim for Saudi Arabia to achieve net-zero emissions by 2060 by G20 pledges (Nurunnabi, 2017; Grand and Wolff, 2020). To achieve this vision, is necessary to understand the link between various sectors that reduce environmental quality. This is because apart from the direct GHG emission from gas and oil production, sectors the consume it such as agriculture, transport among others contribute to rise in GHG emissions. In this article, we analyze the link between energy economic growth, Agriculture, Industry, Energy consumption and oil production and carbon dioxide emissions. To the best of our knowledge, no study has analyzed the effects of these variables. This we believe will bridge the gap in the existing literature and provide the basis for decision making.

## 2. Literature review

Fossil fuel (oil and gas) consumption as non-renewable sources of energy is the key driver of economic growth in some countries (Wang et al., 2023). In fact, modern global economies are kept in motion by energy consumption, and yet economic growth is intensely interconnected with the quality of environment (Ekonomou and Halkos, 2023) which has far reached consequences. Fossil fuels, including oil, and gas, coal account for 75% of GHG emissions, and specifically 90% $CO_2$ emissions globally (Kareem et al., 2023), making them the midpoint of discussion. Striking a sustainable balance between environmental protection, energy consumption and economic growth (EEE) now constitutes the global trinity impetus guiding policy formulation and decisions in most countries (Tong et al., 2020; Şanlı et al., 2023); because the negative balance between the EEE is concomitant with environmental deterioration which is exacerbated by climate change (Ozturk and Acaravci, 2010). Moreover, environmental deterioration is partly linked to increased GHGs emission arising from over dependency on the use of fossil fuel energy (Osobajo et al., 2020; Wang et al., 2023). As result achieving a sustainable balance between economic growth and environmental protection remains the primary vision of nations including Saudi Arabia (Alshuwaikhat and Mohammed, 2017; Abubakar and Dano, 2020). The necessity of achieving a sustainable balance between economic growth and environmental protection is since Saudi Arabia is a major producer and exporter of fossil fuel energy, and therefore among the highest carbon dioxide emitters (Tiwari et al., 2018; Tiwari et al., 2018). Mitigating the rising emissions using renewable energy consumption is one of the strategies employed by top oil producing, marketing and consuming countries to lessen environmental effects. The international standard for reducing emissions needs a long time to be achieved due to the difficulty of reaching a protected environment through the consumption of mainly and large renewable energy. In addition, domesticated and documented empirical evidence of GHG emissions by each country is needed to legitimize the implementation of mitigation strategies domestically (Mahmood, 2022).

Empirical analysis of data between 1985 and 2017 in Eastern Europe, South Asia, East Asia, Central Asia, Southeast Asia and the North and Middle East Africa revealed that economic growth, use of conventional energy, and increase in urbanization principally influenced $CO_2$ emissions with cointegration nexus between the variables in Eastern Europe, South Asia, East Asia, Central Asia, Southeast Asia and the North and Middle East Africa (F. Liu et al., 2023). Wang et al. (2023) investigated the effect of non-renewable and renewable energy consumption on $CO_2$ emissions and economic growth in seven Northeast Asian countries. Results revealed that $CO_2$ emissions were significantly increased by consumption of non-renewable energy and the reverse was true for renewable energy in a long term. Accordingly, Vural (2020) indicated increase in carbon emissions by 0.09% due to rise in consumption of non-renewable energy by 1%, while carbon emissions decreased by 0.015% due to reduction in consumption of non-renewable energy by 1%. Jena et al. (2022) reported deterioration of environmental quality due to use of non-renewable energy in India, Japan and China.Gołas (2023) analyzed fossil fuel, environmental and economic indicators, and $CO_2$ emissions decoupling efforts in Poland between 2004 and 2020. Results demonstrated that $CO_2$ emissions from fossil fuel dropped by 0.7% per year while energy consumption increased by 0.8% annually. The core driver of $CO_2$ emissions was economic growth while reduction was energy intensity. In Mexico, Venezuela, and Colombia, a bidirectional causality linking pollution and energy consumption was reported (Nahrin et al., 2023). Khan et al. (2023) investigated the interconnection between economic growth, renewable energy consumption, natural resources, and $CO_2$ emission in the 35-road initiative and belt countries for a period between 1985 and 2019. Results revealed natural resources and economic growth to have a positive effect on $CO_2$ emissions while significant reduction was registered from renewable energy consumption. Earlier, Tong et al. (2020) reported non-existence of cointegration between energy consumption, economic growth and $CO_2$ emissions in Mexico, Indonesia, China, Turkey except India, and Russia. Conversely, In Korea, Kang et al. (2022) investigated how $CO_2$ and energy reduction affect production efficiency and economic growth. Results revealed that 1% reduction in $CO_2$ reduced the GDP by 0.1%. This implies countries need to establish affordable carbon-neutral policies that will not hurt their economies but at the same time improve environmental quality. In the view of developing countries, analysis of data in Uganda between 1986 and 2018 showed that energy consumption did not $CO_2$ emission while GDP had increased it (Otim et al., 2022). In Kenya, fossil fuels uptake and fossil fuels increased $CO_2$ emissions while urbanization reduced it, suggesting the need for development of clean energy technologies (Otim et al., 2023). A report in South Africa revealed a negative significant link between emissions and energy use (Kareem et al., 2023).

Energy consumption through underdeveloped sectors such as agriculture, manufacturing, urbanization, and other sectors affects emissions because they vary in ways of using energy, its quantities and sources. This is what (Yang et al., 2022; Yahya et al., 2023; Goswami et al., 2023; Altouma et al., 2022) discussed. Yang et al. (2022) examined the impact of energy intensity, industrial transition, and economic growth on $CO_2$ emissions in China for a period between 1980 and 2019. Results demonstrated all the variables were cointegrated with a U-shaped nexus. Moreover, energy intensity and secondary industry added value had a significant positive effect on $CO_2$ emissions. In Indonesia, economic growth, energy consumption and road infrastructure increased $CO_2$ emissions suggesting the need for renewable energy and energy-efficient transportation system (Yahya et al., 2023). A study by

Goswami et al. (2023) in India revealed that energy consumption, trade openness and urbanization positively correlated with $CO_2$ emissions in a long run while at previous lag, $CO_2$ emissions and economic growth were a negatively correlated. In the Philippines, Raihan (2023b) analyzed the link between renewable energy use, industrialization, urbanization, tourism, forest area, agricultural productivity, economic growth, and $CO_2$ emissions. Results showed that $CO_2$ emissions increased by 0.16%, 0.06%, 1.25%, and 0.02% due to 1% increase in economic growth, industrialization, urbanization, and tourism. Altouma et al. (2022) studied the effect of primary energy consumption, agriculture, and economic growth on $CO_2$ emissions in the Czech Republic. Results revealed variables cointegration with a positive correlation between primary energy consumption, agriculture, economic growth, and $CO_2$ emissions. Agriculture and economic growth had a unidirectional Granger causality towards $CO_2$ emissions. $CO_2$ emissions and energy consumption had no Granger causality with economic growth. In Nepal, increased agricultural productivity and use of renewable energy improved environmental quality by reducing $CO_2$ emission while the reverse was true for utilization of fossil fuel energy and economic growth. Reduction of $CO_2$ emission by 0.41% and 3.65% were concomitant with a 1% increase agricultural productivity and use of renewable energy, respectively in a long run. Meanwhile rise by 1% in both fossil fuel energy use and economic growth increased emissions by 0.6% each. In Vietnam, Raihan (2023a) assessed the impact of agricultural added value, economic growth, and energy use, on $CO_2$ emissions. The results indicated that the increase in carbon dioxide emissions resulted from energy use and economic growth. This increase in emissions led to environmental deterioration, while agricultural added value led to a reduction in carbon dioxide emissions, which indicates that agricultural development leads to an improvement in environmental quality. In Bangladesh, reduced agricultural productivity, energy use, urbanization, and economic growth increased $CO_2$ emissions. Seemingly, agriculture being the key component of human livelihood becomes critical element in GHGs emissions in addition to other sectors. In fact, Qiao et al. (2019) noted that agriculture is the second global leading emitter of GHG due to burning of biomass, agricultural machinery, and utilization of fossil fuel-based fertilizers. The impact of energy use, economic growth, urbanization, and other factors affect the quality of the environment. The results of studies varied in the impact of each of these variables on the environment, which allowed the continuation of investigations to give the best proposals for policies to mitigate risks and preserve environmental quality (Minh et al., 2023).

The aspiration KSA like any other UN member states is to achieve SDGs agenda by 2030 (AlArjani et al., 2021), as such several empirical studies have been undertaken. Raggad (2018) examined the existence of long-run connection between energy use, economic growth, urbanization, and $CO_2$ emissions between 1971 and 2014. Results revealed EKC hypothesis to be non-valid as GDP and pollution nexus was positive. However, a negative significant impact was revealed between urbanisation and $CO_2$ emissions. Dkhili and Dhiab (2020) analyzed the nexus between energy consumption on $CO_2$ emissions and economic growth between 1990 and 2018. Results revealed a causal relationship between $CO_2$ emissions and energy consumption to be unidirectional in the long term, suggesting the $CO_2$ emissions and energy consumption did not drive economic growth. Accordingly, Alajlan and Alreshaidi (2023) analyzed the connection between economic growth and $CO_2$ emissions, and urbanization for the period between 1985 and 2019. Results demonstrated that 1% increase in economic growth caused rise in $CO_2$ emissions by 0.15%. A unidirectional causal relationship existed between variables with 0.004% and 0.3% increase in urbanization and $CO_2$ emissions attributed to 1% increase in GDP. In terms of industry, Matar and Elshurafa (2017) reported the cement industry as the main contributor of $CO_2$ emissions balance in Saudi Arabia. Authors argued that regardless of the preference, $CO_2$ emissions could be abated by charging a minimum carbon price. Meanwhile, asymmetry analysis by Mahmood (2022) on GCC countries $CO_2$ emissions due to oil and natural gas consumption revealed that both increasing and decreasing oil consumption had positive effect on $CO_2$ emissions. Given that the main comparison in the study was the effect of each of the oil consumption on carbon dioxide emissions compared to the effect of natural gas consumption on carbon dioxide emissions, the results showed that the increase in oil consumption led to a rise in carbon dioxide emissions more than the increase in carbon dioxide emissions resulting from Increased natural gas consumption in the UAE, Oman, Kuwait and Saudi Arabia. In fact, Alshehry and Belloumi (2015) confirmed existence of a long-run nexus between energy price, energy consumption, $CO_2$ emissions, and economic growth in Saudi's economic growth. Contrariwise, Alkhathlan and Javid (2013) reported an increasing monotonic link between per capita income and per capita $CO_2$ emissions for electricity and oil and consumption models suggesting that economy of Saudi Arabian economy switched from oil to gas consumption. The reduction in $CO_2$ emissions would be concomitant with increase in per capita income in terms of transport. Alkhathlan and Javid (2015) analyzed the impact of oil consumption in transport sector on environmental quality between 1972 and 2013. Results revealed a nonlinear and stochastic trend for $CO_2$ emissions. There was a positive significant elasticity of $CO_2$ emissions in relation to transport oil consumption and total oil consumption. Positive progress in income increased $CO_2$ emissions but the opposite was not true for both models.

Overall aggregated literature by Vosviewer software analysis revealed that studies concentrated in unravelling empirical evidence of the nexus between $CO_2$ emissions and variables such as economic growth, energy consumption, urbanisation, and income and energy consumption Fig. 1. It is evident that limited studies included agriculture sector and policy. Our study therefore differs in that it tracks $CO_2$ emissions from sectors such as energy (oil and gas) production and consumption, energy economic growth, industry, and agriculture and links them dynamics to of Saudi Arabia's Vision 2030 (policy) using robust techniques. This increases the scope of empirical evidence available for policy planners in KSA to make environmental impact assessments.

## 3. Methodology

### 3.1. Data collection and preliminary analysis

Available greenhouse gas emissions (GHGs) data from different sectors were collected from Our World in Data Table 1. Data include GHGs from different sectors, measured in tonnes of carbon dioxide-equivalents (1990–2019), Methane emissions from different sectors, measured in tonnes of carbon dioxide-equivalents (1990–2019), and Nitrous oxide emissions from different sectors, measured in tonnes of carbon dioxide-equivalents (1990–2019).

Other economic data were collected from different sources for the period 1970 to 2020, as shown in Table 1. Data were chosen to cover most of the economic activities in the Kingdom. Interestingly, the World In Data Database used data from the Global Carbon Project and the Shift Data Portal to obtain information on oil production and $CO_2$ emissions.

To summarize the data and have a full overview of it, descriptive statistical analyses were implemented. Which include minimum, maximum, mean, and standard deviation. Also, box-and-whisker plots were used for visual summery of the data (mean, median, etc.). On the other hand, the box-and-whisker plots were also used to compare emission between different sectors. To capture the trend, whether it is increasing or decreasing over the time series (1990–2019), the Mann-Kendall (MK) test and Sen's Slope estimator were used (Mann 1945). The MK test is a nonparametric test that is not affected by outliers and can capture the trend. For this test, the null hypothesis (H0) is that there is no trend in the series, and the alternative hypothesis (Ha) is that there is a trend in the series. Additionally, the Principal Component Analysis (PCA) were used to summarize the observed emission sources into fewer representative variables called principal components (PCs). These PCs

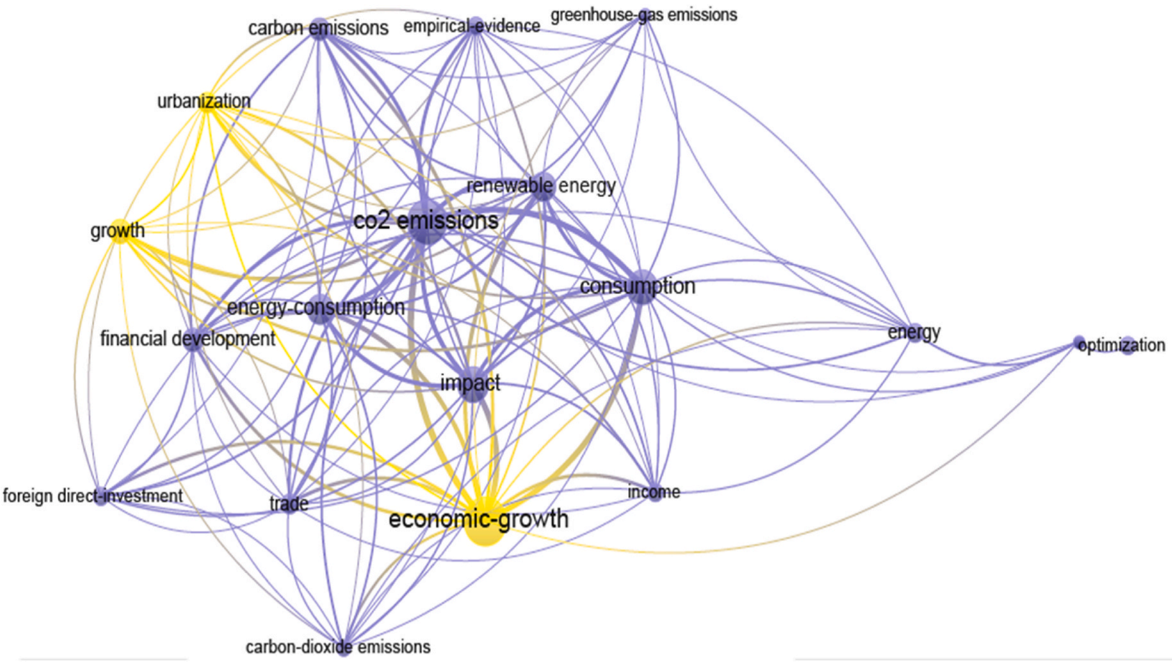

**Fig. 1.** Aggregation of principle variables contributing to $CO_2$ emissions in Saudia Arabia between 1970 and 2020 based on Vosviewer software bibliographic analysis.

**Table 1**
Data source and its description.

| Variable | Abbreviation | Unit | Time span | Link |
|---|---|---|---|---|
| Greenhouse gas emissions | GHGs | Tonnes of carbon dioxide-equivalents | 1990-2019 | https://ourworldindata.org/co2/country/saudi-arabia |
| Annual $CO_2$ emissions | $CO_2$ | Tonnes | 1970-2020 | $CO_2$ emissions - Our World in Data |
| Economic growth | GDP | constant 2015 US$ | 1970-2020 | GDP (constant 2015 US$) - Saudi Arabia \| Data (worldbank.org) |
| Agriculture, forestry, and fishing, value added | AGR | constant 2015 US$ | 1970-2020 | Agriculture, forestry, and fishing, value added (constant 2015 US$) - Saudi Arabia \| Data (worldbank.org) |
| Industry (including construction), value added | IND | constant 2015 US$ | 1970-2020 | Industry (including construction), value added (constant 2015 US$) - Saudi Arabia \| Data (worldbank.org) |
| Services, value added | SERV | constant 2015 US$ | 1970-2020 | Services, value added (constant 2015 US$) - Saudi Arabia \| Data (worldbank.org) |
| Oli Production | OILP | Barrels/Year | 1970-2020 | Statistical Report (sama.gov.sa) |

are linear combinations of the original data and capture most of its variability correlated. This is a statistical approach that convert observed emission sources (variables) into PCs through orthogonal transformation.

Econometric procedure starts by evaluating the stationary of each variable by executing the unit root. It gives the steps further by selecting one out of the different Econometric options. If all variables are stationary either ordinary least square or vector autoregressive models can be used. ordinary least square is used to the relationship between the studied variables can be ascertained using the ordinary least square approach. While the dependent and independent regressors can use the historical values to provide feedback or reverse causality by using the Vector Autoregressive model. This model implies that all regressors are endogenous. We cannot use the two aforementioned methods for non-stationary time series due to the possibility of giving unreal results when implementing the regression test by showing a statistically significant relationship between two variables even though they are not related. Added to this is the inability to accurately clarify the long-term clarity relationship (Shrestha and Bhatta, 2018).

To address these difficulties, Engel and Granger created a new test aimed at analyzing relationships between non-stationary variables. Updates came from Johansen and Juselius for that test. The correlation between the rank of the matrix and its distinctive roots forms the basis of this test procedure. Hence, if all variables are nonstationary, we can use Johansen cointegration test (Robert 1987; Johansen and Juselius 1990).

Mixed variables in the stationary level I0 and I1 require special treatment, so another model was proposed for that scenario. An ordinary least square based model called autoregressive distributed lag was created. Autoregressive distributed lag will be followed by dynamic error correction model that preserves long-term information while describing short-term dynamics with the long-term equilibrium. It circumvents OLS issues such as spurious relationship (Pesaran, and Shin, 1995).

ARDL modeling is illustrated as following:

$$y_t = a + \beta_{x1} + \delta_{z1} + E_t \tag{1}$$

It is followed by the error correction of the ARDL which is illustrated as following:

$$\Delta y_t = a_0 + \sum_{I=i}^{P} \beta_t \Delta y_{t-i} + \sum_{I=i}^{P} \delta_t \Delta x_{t-i} + \sum_{I=i}^{P} \pounds \Delta z_{t-i} + \lambda 1 y_{t-1} + \lambda 2 x_{t-1} + \lambda 3 z_{t-1} + \mu_t \tag{2}$$

The short run dynamics of the model are represented by the first equation. The second one stands for a long-term partnership. The absence of a long-term relationship is the null hypothesis (Pesaran, and Shin, 1995).

### 3.2. Autoregressive distributed lag model (ARDL)

The ARDL empirical model investigates the interaction between $CO_2$ emissions and other studied variables (i.e., economic growth, agriculture, industry, services, and oil production). The functional relationship is:

$$CO_2 = F(GDP, AGR, IND, SERV, OILP) \tag{3}$$

$CO_2$, GDP, AGR, IND, SERV, OILP represent carbon dioxide emissions (tonnes), economic growth (constant 2015 US$), Agriculture (constant 2015 US$), Industry (constant 2015 US$), Service (constant 2015 US$), and oil production (Barrels/Year).

Hence, the stochastic form of the model is:

$$CO_2 = a_0 + a_1\, GDP + a_2 AGR + a_3 IND + a_4 SERV + a_5 OILP + \mu_t \tag{4}$$

Where = $a_0$, $a_1$, $a_2$ , $a_3$, $a_4$ and $a_5$ are coefficients for intercept, GDP, AGR, IND, SERV, OILP, respectively, and $\mu_t$ = the stochastic term.

To interpreting the elasticities in Eq. (3), the natural logarithmic transformation was applied. The following equation is the result of the transformation:

$$Ln\ CO_2 = a_0 + a_1\ LnGDPt + a_2\ LnAGRt + a_3\ LnINDt + a_4\ LnSERVt + a_5\ LnOILPt \tag{5}$$

Where = $a_0$, $a_1$, $a_2$ , $a_3$, $a_4$ and $a_5$ are coefficients.

Unit root testing was implemented as a first step to verify the necessary econometric analysis and to provide the next steps for achieving the paper's objective. To determine whether the variables had unit roots, the widely known Augmented Dickey-Fuller method was applied (Dickey and Fuller, 1979). In 1979, Dickey and Fuller defined the primary and alternative hypotheses: $H_0$ indicates that the series is not stationary and has a unit root, while ADF is an alternative indication that the series is stationary. The ADF stationary results and levels determine the further steps.

In this context, Johansen and Juselius (1990); and Engle and Granger (1987) had restricted the cointegration steps to variables of the same order of integration, I (1). Whereas Pesaran and Smith's suggested test in 2001, the Autoregressive Distributed Lag, was the right one. When the variables have integration orders of I(0), I(1), or a mixture of both, without any I(2) or above, ARDL can be employed. The following is the ARDL model representation:

$$\begin{aligned}\Delta CO_{2t} = {} & a_0 + \sum_{I=i}^{P} a_{1t}\ \Delta CO_{2t-1} \sum_{I=i}^{P} a_{2t} \Delta GDP_{t-1} + \sum_{I=i}^{P}\ a_{3t} t \Delta AGR_{t-1} \\ & + \sum_{I=i}^{P} a_{4t} \Delta IND_{t-1} + \sum_{I=i}^{P} a_{5t} \Delta SERV_{t-1} + \sum_{I=i}^{P} a_{6t} \Delta OILP_{t-1} + \lambda 1 CO_{2t-1} + \lambda 2 GDP_{t-1} + \lambda 3 AGR_{t-1} + \lambda 4 IND_{t-1} + \lambda 5 SERV_{t-1} + \lambda 6 OILP_{t-1} + E_t\end{aligned} \tag{6}$$

Δ is the difference operator: p indicates lag length; $a_0$ is the constant term; $a_{1t}$, $a_{2t}$, $a_{3t}$, $a_{4t}$, $a_{5t}$, and $a_{6t}$ are error correction dynamics; λ1, λ2, λ3, λ4, λ5, and λ6 are long-term coefficients; $E_t$ is the white noise disturbance term.

As indicated by Wooldridge (2015), the null hypothesis suggests that there is no cointegration. This will be evident when the F-statistic is lower than I(0). In contrast, the null hypothesis is rejected when the F-statistic is higher than I(1), indicating cointegration. The inclusiveness of the cointegration test can be shown when the F-statistic value is between I(0) and I(1).

Post-estimation model diagnostic can be performed after assessing the ARDL results and as a required quality check. Testing for both the existence and absence of heteroskedasticity is that primary goal. When $H_0$ is present, normalcy and the absence of heteroskedasticity are both present. Additionally, the Cusum test is helpful for the stability assessment as per Wooldridge (2015). The research paper did not require to unitize non-Linearity test similar to other studies (Alola, and Onifade, 2022; Ahmadi, 2021; Phiri et al., 2021; Menegaki, 2019) that used the same approach authors used in this research.

## 4. Results and discussion

### 4.1. An overview of GHGs emission in KSA

In KSA there is many sources for GHGs emissions as can be seen in Figs. 2 and 3. However, the contribution in emissions is varied among sectors. Fig. 2 showed that the highest contributor to GHGs emissions is electricity and heat sector (33%), followed by transportation sector (18.9%), then emission from the Fugitive (15.2%). For methane emission, the majority emitted from Fugitive 73.3%, followed by waste sector 23.7% and the agricultural sector 27% (Fig. 2). Interestingly, 77.3% of Nitrous oxide emissions originated from the agriculture sector, followed by waste sector by 27.7% (Fig. 2).

Descriptive analysis of GHGs data (1990–2019) reveal that the average emission from electricity and heat sector was 161443665.82 ± 67940644.11 tonnes of carbon dioxide-equivalents, and 91008000.56 ± 35445661.23 tonnes of carbon dioxide-equivalents from transportation. However, the lower emission was recorded in agriculture (5801333.33 ± 455455.33 tonnes of carbon dioxide-equivalents), and building (3845666.68 ± 785241.81 tonnes of carbon dioxide-equivalents) sectors (Fig. 3). The main source of methane emission was fugitive with an average 65767999.77 ± 9702484.33 tonnes of carbon dioxide-equivalents (1990–2019) (Fig. 3). However, the agricultural sector was the main emitter of nitrous oxide (1990–2019) with an average 3348333.33 ± 294186 tonnes of carbon dioxide-equivalents.

The MK test revealed significant ($p < 0.05$) positive increase of GHGs emissions from all sectors across the KSA. The highest increased were captured at the Electricity and heat 7345454.47 tonnes of carbon dioxide-equivalents/year ($p < 0.05$). for the methane emissions, a positive significant increase was also captured from all sectors, however, the highest increased one was noticed at the fugitive by 1071817.9183 tonnes of carbon dioxide-equivalents/year ($p < 0.05$). Interestingly, the nitrous oxide emission increased by 4999.99 tonnes of carbon dioxide-equivalents/year, although the increase was not statistically significant. Overall, all monitored sectors across the country exhibited an increasing trend of GHG emissions (Fig. 4).

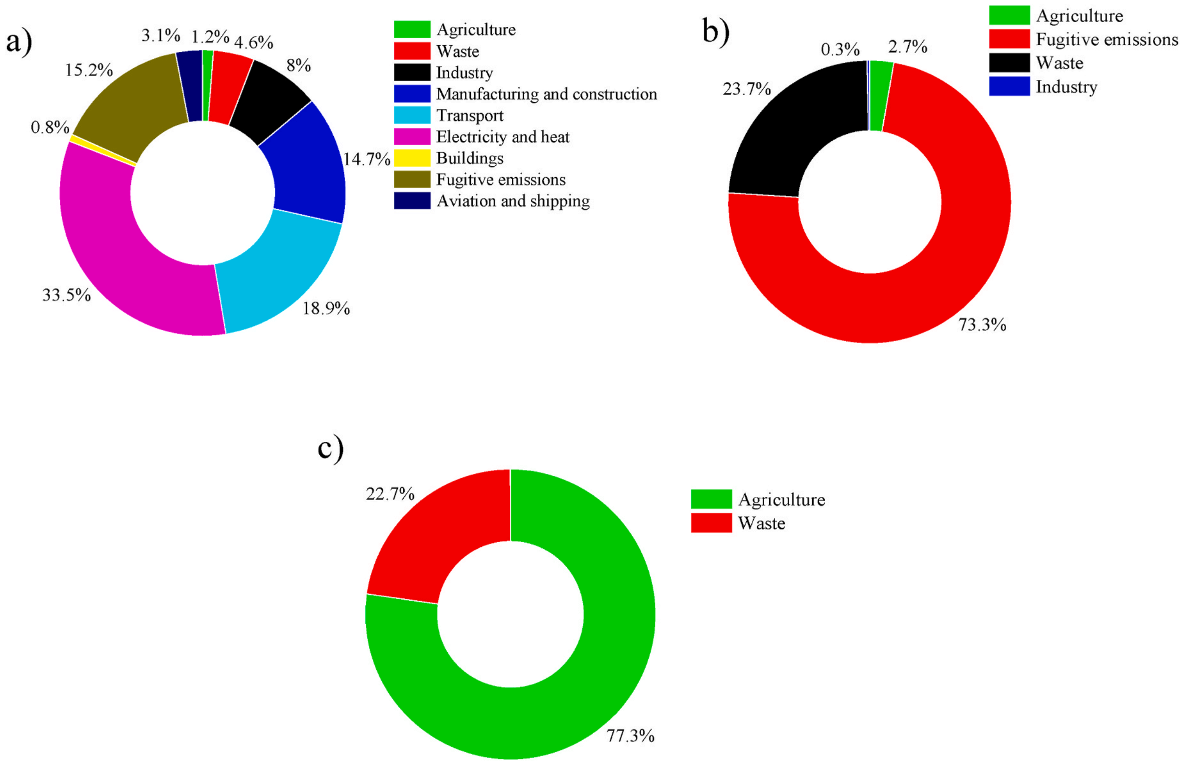

**Fig. 2.** Pie chart of the sources of GHGs in KSA (1990–2019): a) % GHGs emissions from different sectors, b) % methane emission from different sectors, c) % of nitrous oxide from different sectors.

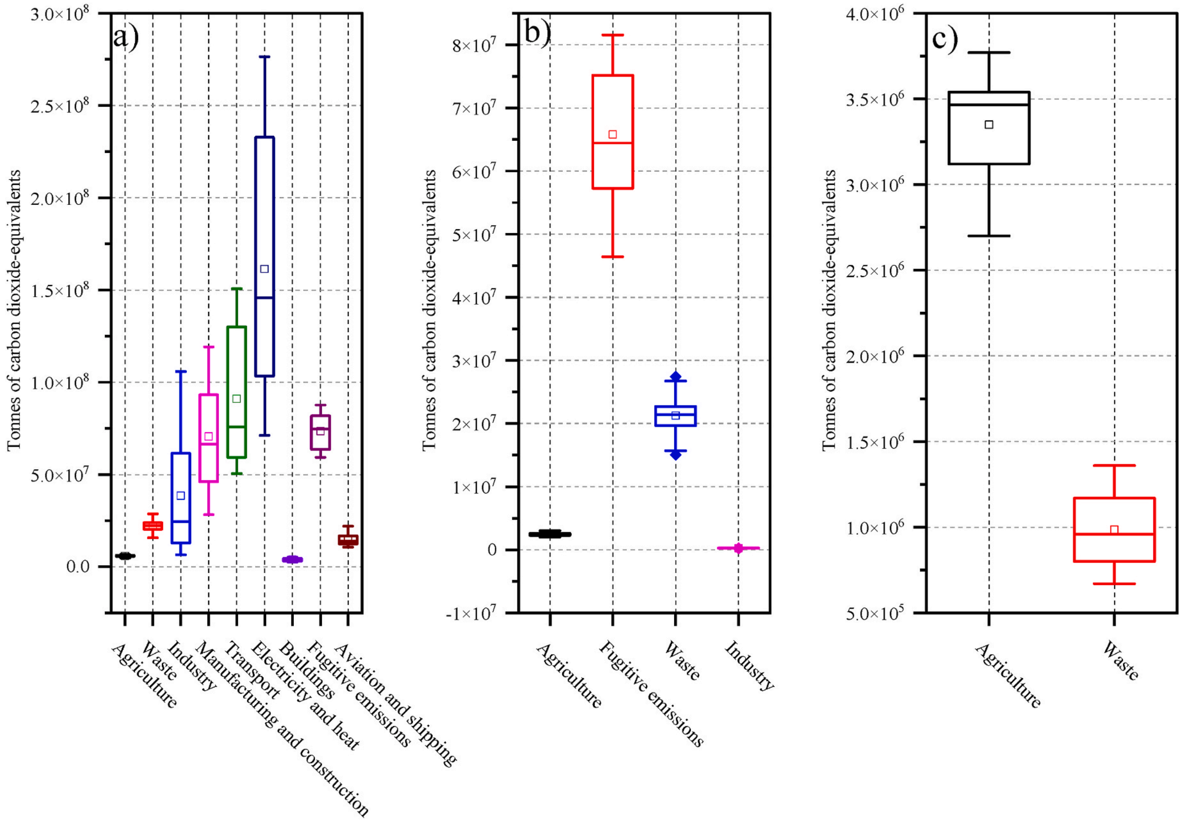

**Fig. 3.** Box plot of the different sources of GHGs in KSA between 1990 and 2019: a) total GHGs emissions from different sectors, b) methane emission from different sectors, c) of nitrous oxide from different sectors (□: mean, —: median).

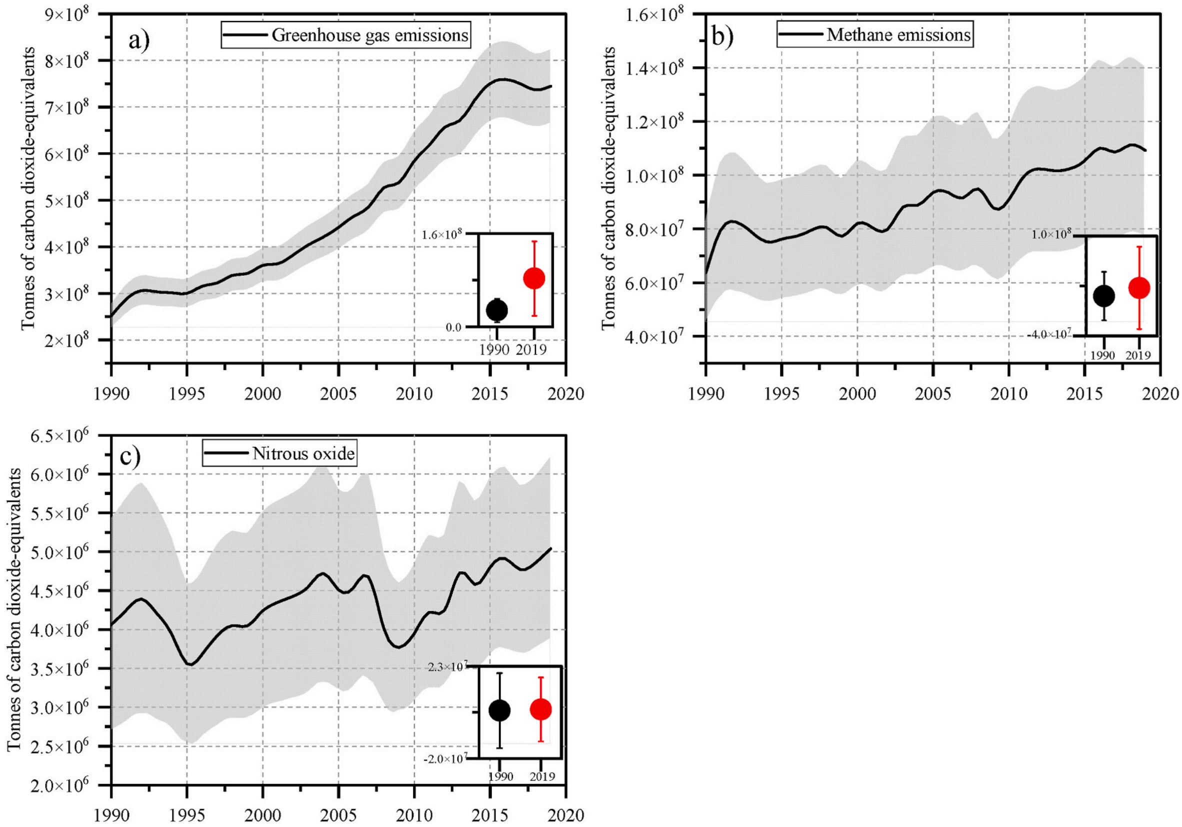

**Fig. 4.** Temporal evolution of GHGs emission across the KSA between 1990 and 2019: **a**) total GHGs emissions from different sectors, **b**) methane emission from different sectors, **c**) nitrous oxide from different sectors (black line represents the average of emission from all sectors, gray shadow represents the standard deviation; black I-shape box plot represents emission in 1990, red I-shape box plot represents emission in 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The PCA analysis of total GHGs emissions reveals that PC1 explained 79.95% of the total variance, while PC2 explained 9.4% of the total variance (Fig. 5). However, Fig. 5 showed that emissions from agriculture, fugitive, and aviation and shipping are more corelated with each other and could be clustered alone, and more influenced by PC2. While waste, industry, manufacturing and construction, transport, electricity and heat, buildings are more associated with each other, and more influenced by PC1 (Fig. 5).

### 4.2. Unit root test

For each variable in this empirical investigation, we used Augmented Dickey-Fuller Stationary unit root tests to look for stationarity at the appropriate level. The results in Table 2 show that AGR, and SERV are stationary at their first differences, while $CO_2$, GDP, IND, OILP are stationary at their level.

To double confirm that, another unit root test was implemented. Philips-Perron confirmed that we have a mixture of both I(0), I(1). $CO_2$. GDP, and SERV are stationary at their level, and AGR & OILP are stationary at their first differences as per Table (3).

### 4.3. Autoregressive-distributed lag ARDL

The short-term presence was confirmed using the ARDL estimate. Table 4 indicates that GDP, Agriculture, Industry, Services, and oil production have short-term effects on the environment through carbon dioxide emissions. Table 5 illustrates the convergence of $CO_2$ emissions, GDP, agriculture, industry, Services, oil production to a long-run equilibrium at a speed of an absolute value of 1.11, which is statistically significant with a probability of less than 5 percent. This indicates that these variables will attain a long-term equilibrium in 0.9002 years when expressed in time. With an F-statistic of 6.0898 over the I(1) bounds of 3, 3.38, 3.73, and 4.15. at 10, 5, 2.5, and 1 percent, respectively, the cointegration results supported this. The relevant I(0) bound values were 2.08, 2.39, 2.7, and 3.06, respectively (at the exact percentages as the I(1) bounds), and the F-statistic was higher than these values.

The results in Table 6 show that the GDP, Agriculture, Industry, Oil Production coefficients are statistically significant. Therefore, GDP, Agriculture, services and oil production contribute to increases in $CO_2$ emissions. While industry contributes to decrease in $CO_2$ emissions. The estimates also show that an increase in GDP of 1 percent increases $CO_2$ emissions by 3.46 percent, an increase in agriculture of 1 percent increases $CO_2$ emissions by 0.26 percent, an increase in oil production of 1 percent increases $CO_2$ emissions by 4.04 percent, and an increase in Service of 1 percent decreases CO2 emissions by 0.79 percent. However, an increase in industry of 1 percent decreases $CO_2$ emissions by 7.25 percent.

The model's R-squared value showed that it was ideally proportional since the GDP, industry, agriculture, services and oil production regressors explained 75.46% of the variation in the variable ($CO_2$ emissions) (see Table 5). Additionally, the same finding was supported by the F-statistic from the same table, which demonstrated statistical significance due to its probability of less than 5%.

### 4.4. Diagnostic tests

The results of the post-estimation diagnostic tests for autocorrelation, heteroskedasticity, and normality are shown in Table 7. Table 7 displays the results of correlation, heteroskedasticity, and normality. The tests return, in that order, p - values of 0.2920, 0.8497, and 0.7116,

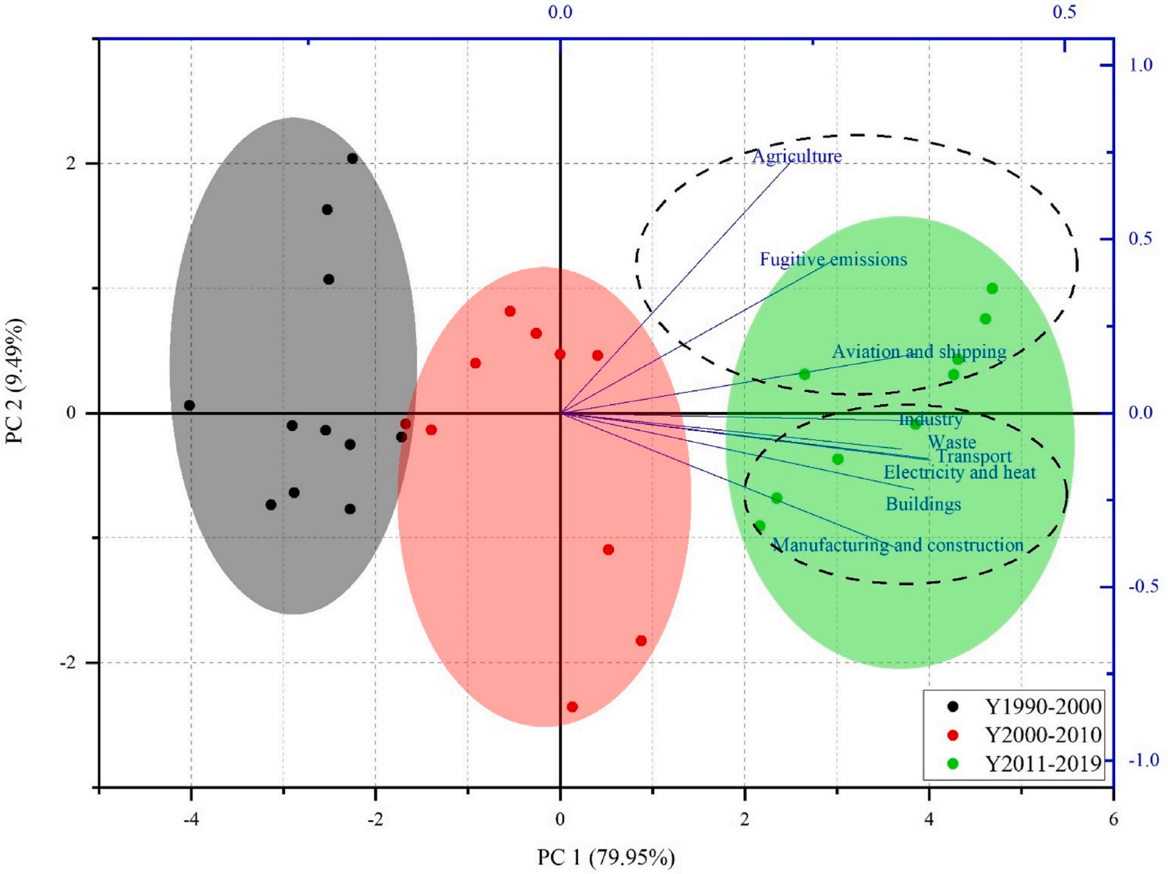

**Fig. 5.** Biplot of PCA for total GHGs emission (1990–2019) with a 95% level of confidence ellipse.

**Table 2**
ADF Unit root results.

| Variable | Level | | First deference | |
|---|---|---|---|---|
| | ADF Statistics | Result | ADF Statistics | Result |
| $LCO_2$ | −3.789** | Stationary | – | – |
| LAGR | −1.938 | Non-Stationary | −4.148** | Stationary |
| LGDP | −3.820** | Stationary | – | – |
| LIND | −3.380** | Stationary | – | – |
| LSERV | −2.874 | Non-Stationary | −1.916** | Stationary |
| LOilP | −3.772** | Stationary | – | – |

**significance at the 5% level.

**Table 3**
Philips-Perron Unit root results.

| Variable | Level | | First deference | |
|---|---|---|---|---|
| | PP Statistics | Result | PP Statistics | Result |
| LCO2 | −3.733** | Stationary | – | – |
| LAGR | −0.984 | Non-Stationary | −6.741** | Stationary |
| LGDP | −3.201** | Stationary | – | – |
| LIND | −2.968 | Non-Stationary | −5.876** | Stationary |
| LSERV | −1.916** | Stationary | – | – |
| LOilP | −2.962 | Non-Stationary | −2.871** | Stationary |

**significance at the 5% level.

all of which are greater than 5%, and show that the H0 is not accepted. Consequently, the model choice for the analysis and interpretation was correct.

The stability of the model was evaluated using the CUSUM test, and the outcomes were displayed. The blue line between the parallel red lines in the output graphic indicates that the model has shown to be stable (Fig. 6).

**Table 4**
ARDL estimation output.

| Variable | Coefficient | Std. Error | t-Statistic | Prob.* |
|---|---|---|---|---|
| LCO2(-1) | 0.319404 | 0.171271 | 1.864905 | 0.0735 |
| LCO2(-2) | 0.131426 | 0.180345 | 0.728747 | 0.4727 |
| LCO2(-3) | −0.213134 | 0.160354 | −1.329142 | 0.1953 |
| LCO2(-4) | −0.348575 | 0.148446 | −2.348166 | 0.0267 |
| LGDP | 3.844257 | 1.728472 | 2.224078 | 0.035 |
| LAGR | 0.242298 | 0.247047 | 0.980781 | 0.3357 |
| LAGR(-1) | −0.68567 | 0.319656 | −2.145027 | 0.0415 |
| LAGR(-2) | 0.44072 | 0.274466 | 1.605735 | 0.1204 |
| LAGR(-3) | 0.297215 | 0.18907 | 1.571986 | 0.128 |
| LIND | −3.246754 | 2.668818 | −1.216551 | 0.2347 |
| LIND(-1) | 1.2879 | 1.811981 | 0.710769 | 0.4836 |
| LIND(-2) | 0.180526 | 1.891734 | 0.095429 | 0.9247 |
| LIND(-3) | −6.27659 | 2.201016 | −2.851678 | 0.0084 |
| LSERV | −0.561593 | 0.68941 | −0.814599 | 0.4227 |
| LSERV(-1) | −0.46376 | 0.805525 | −0.575724 | 0.5698 |
| LSERV(-2) | 1.91151 | 0.581876 | 3.285081 | 0.0029 |
| LOIL | 0.68988 | 1.479219 | 0.466381 | 0.6448 |
| LOIL(-1) | −1.221158 | 1.427666 | −0.855353 | 0.4002 |
| LOIL(-2) | 0.131162 | 1.458805 | 0.089911 | 0.929 |
| LOIL(-3) | 4.890227 | 1.699661 | 2.877178 | 0.0079 |
| C | 1.131947 | 3.040846 | 0.372247 | 0.7127 |

## 5. Discussion

### *5.1. GHGs emissions in KSA: sources and impact*

Providing empirical evidence of sectoral GHGs emissions is an impetus to development and/or adjustment of mitigating strategies and/or policies. Our study shows a positive increase in GHGs emissions with the highest contributor being electricity and heat sector followed by transportation sector, fugitive and the lowest being in agriculture. These

**Table 5**
ARDL error correction regression.

| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
|---|---|---|---|---|
| D(LCO2(-1)) | 0.430283 | 0.115793 | 3.715962 | 0.001 |
| D(LCO2(-2)) | 0.561709 | 0.125659 | 4.470103 | 0.0001 |
| D(LCO2(-3)) | 0.348575 | 0.122508 | 2.845323 | 0.0085 |
| D(LAGR) | 0.242298 | 0.166493 | 1.455306 | 0.1576 |
| D(LAGR(-1)) | −0.737935 | 0.177366 | −4.16051 | 0.0003 |
| D(LAGR(-2)) | −0.297215 | 0.145062 | −2.048882 | 0.0507 |
| D(LIND) | −3.246754 | 1.241092 | −2.616046 | 0.0146 |
| D(LIND(-1)) | 6.096064 | 1.445534 | 4.21717 | 0.0003 |
| D(LIND(-2)) | 6.27659 | 1.655133 | 3.792197 | 0.0008 |
| D(LSERV) | −0.561593 | 0.413288 | −1.35884 | 0.1859 |
| D(LSERV(-1)) | −1.91151 | 0.507687 | −3.765139 | 0.0009 |
| D(LOIL) | 0.68988 | 0.843734 | 0.817651 | 0.421 |
| D(LOIL(-1)) | −5.021389 | 1.166583 | −4.304355 | 0.0002 |
| D(LOIL(-2)) | −4.890227 | 1.281162 | −3.817024 | 0.0008 |
| CointEq(-1)* | −1.110879 | 0.153365 | −7.243355 | 0 |
| R-squared | 0.754629 | Mean dependent var | 0.040088 | |
| Adjusted R-squared | 0.647279 | S.D. dependent var | 0.112443 | |
| S.E. of regression | 0.066781 | Akaike info criterion | −2.320925 | |
| Sum squared resid | 0.142708 | Schwarz criterion | −1.730452 | |
| Log likelihood | 69.54173 | Hannan-Quinn criter. | −2.098726 | |
| Durbin-Watson stat | 1.843057 | | | |
| Test Statistic | Value | Signif. | I(0) | I(1) |
| F-statistic | 6.089825 | 10% | 2.08 | 3 |
| K | 5 | 5% | 2.39 | 3.38 |
| | | 2.5% | 2.7 | 3.73 |
| | | 1% | 3.06 | 4.15 |

**Table 6**
Long-run relationship and coefficients towards $CO_2$.

| Variable | Coefficient | Std error | T-statistics | Prob |
|---|---|---|---|---|
| LGDP | 3.46 | 1.51 | 2.29 | 0.0303 |
| LAGR | 0.26 | 0.06 | 3.91 | 0.0006 |
| LIND | −7.25 | 2.44 | −2.96 | 0.0063 |
| LSERV | 0.79 | 0.36 | 2.17 | 0.0390 |
| OILP | 4.04 | 1.32 | 3.05 | 0.0052 |
| C | 1.01 | 2.77 | 0.36 | 0.7164 |

**Table 7**
Diagnostic tests.

| Problem | Test | P-Value |
|---|---|---|
| Serial correlation | Breusch-Godfrey LM | 0.2920 |
| Heteroskedasticity | Breusch-Godfrey LM | 0.8497 |
| Normality | Histogram (Jarque – Bera) | 0.7116 |

results are similar to, Alajmi (2021) had reported that increasing GHGs emissions were concomitant with energy consumption in sectors such as manufacturing, transport, and electricity depicting the need for improvement of energy efficiency. Recently, Akinpelu et al. (2023) reported that $CO_2$ emissions from energy sector rose by 300% in 2019 compared to 1990. With increasing economic growth and industrialization, consumption of fossil fuel is likely to increase and consequently the emissions. Mahmood (2022) revealed that rising oil consumption had high $CO_2$ emissions than increased natural gas consumption in Saudi Arabia. Averting this would mean use of renewable energy and increased energy efficiency. However, Qing et al. (2023) noted that exploring asymmetric behaviour of renewable energy, electricity energy efficiency, and economic growth indicators like GDP based on validated empirical data is necessary before implementation of such strategies and/or policies. Expansion of renewables lower industrial GHG emissions due to supply of low carbon energy such as solar power. This could also contribute to reduction of fugitive emissions by eliminating leakage in the energy system (Lee and Erickson, 2017).

GDP, Agriculture, Industry, Oil Production coefficients are statistically significant. Therefore, GDP, Agriculture, services and oil production contribute to increases in $CO_2$ emissions. While industry contributes to decrease in $CO_2$ emissions. According to our findings, some researchers are similar (Z. Liu et al., 2023), but the distribution of $CO_2$ emissions in 2022 across different sectors follows similar trends seen in previous years. Specifically, the power sector contributed 39.3% to the total emissions, contrary to our findings industry accounted for 28.9%, ground transportation for 17.9%, residential sources for 9.9%, international bunkers (including international aviation and shipping) for 3.1%, and domestic aviation for 0.9%. The main source of nitrous oxide was agriculture though being the least contributors of an overall GHGs, an increase in agriculture of 1 percent increases $CO_2$ emissions by 0.26 percent. This corroborates with the previous results of Alajmi (2021) that agriculture recorded the least (1.50%) emissions. However, being a food powerhouse that sustains the global population, and uses considerable amount of energy and natural resources (Sarkodie et al., 2019), agriculture cannot be ignored when it comes to GHGs emissions because no country survives without food. According to Raihan et al. (2023), a substantial amount of energy is consumed by intensively mechanized agricultural sector worldwide. Therefore, use of modern and sustainable practices is needed in the whole agriculture production lifecycle (Sarkodie et al., 2019). According to Mahmood et al. (2019), rise in the share of agriculture sector in the economy positively affects environment by decreasing per capita $CO_2$ emissions while the reverse is true. Overall, the path to sustainable green growth and mitigation of climate change requires reduction in undesirable exogenous impacts of energy generation which are not costless (Pilo 2017). Therefore, consideration of the associated costs, and far-reaching effects of climate change have to be reflected by policymakers during development of economic growth plans to attain sustainable development (Alajmi, 2021).

Evidently, our findings highlight the significant impact of various sectors on $CO_2$ emissions. Notably, these impacts vary across regions in the world, underscoring the necessity for tailored policies and plans aligned with each country's circumstances. In the case of Saudi Arabia, it is crucial to assess the sector-specific effects within the country and develop corresponding policies in successful countries to address challenges. This approach is pivotal in formulating robust strategies aimed at reducing $CO_2$ emissions.

### *5.2. Industrial sector and renewable energy initiative for sustainability*

Around 15% of the GDP of the Kingdom of Saudi Arabia is made up of industry. It consists of a variety of industries, including those related to construction, transformation, and other fields. Numerous activities, including maintenance, power, engineering design, operational project implementation, road building, sanitation, mechanical, electrical, and industrial activities, gardening, and different maintenance, are included in the construction sector (Almutairi et al., 2018). Leading environmental organizations and businesses have released specific environmental legislation over the past millennium. Where Aramco developed regulations referred to as Saudi Aramco, which contained numerous measures, the most notable of which are dedicated to reducing marine pollution. In parallel, the Jubail Industrial Cities Royal Commission issued environmental laws in 1999 that are solely applicable to facilities there. Since the turn of the millennium, the Kingdom of Saudi Arabia has been issuing laws and legislation to keep up with the need for environmental protection around the world. The first environmental law, which took three years to obtain the executive details for, was released in 2001 and allowed the Saudi Council of Ministers to approve environmental requirements and standards that must be met by industrial activities to protect water, soil, and air (Mansour et al., 2019).

The Kingdom established stringent guidelines and regulations for hazardous waste produced by industry as a follow-up to the 1989 Basel Agreement, in which it took part in the discussion of hazardous waste and its disposal (Document No. 01–2002). The procedures were finished

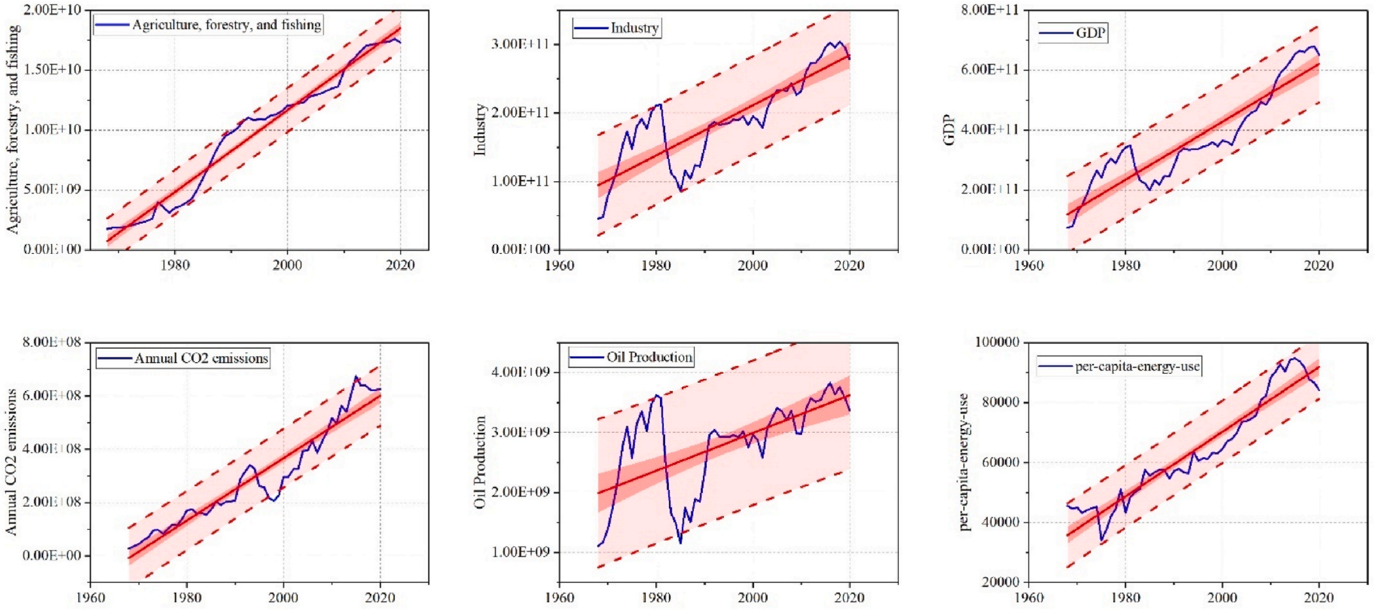

**Fig. 6.** Results of CUSUM test for studied variables.

in 2012, and the following environmental requirements for material recovery and waste recycling were established: ambient air standard; mobile emission standard (Mansour et al., 2019).

Two significant industry-related efforts, the industrial cluster standards project, and the initiative to strengthen regulations and the legislative environment in the industrial sector, were later revealed when the Kingdom's Vision 2030 was unveiled. The first focuses on industrial clusters to identify the rules, criteria, and standards that must be in place for the growth of industrial sectors and to involve the private sector in the establishment of rules and technical requirements. To ensure that the systems of other pertinent authorities are compatible with the industrial sector, the second project involved networking between ministries (Unified National Platform. 2023; Ministry of Industry and Mineral resources, 2023).

And because mining is a part of the business, the Kingdom endeavoured to build a comprehensive and accurate geological database with the goal of growing the mining industry and boosting the nation's gross domestic product with its products. There have been developed technical guidelines for acquiring mining licenses. Afterward, the mining industries will be given the go-ahead to implement technical recommendations to assure the attainment of sustainability in this industry. The publication of technical guidelines on the best utilization of mineral resources in contemporary projects came next (Unified National Platform GOV.SA).

Energy is one of the primary inputs to the industry, thus the Saudi Ministry of Energy has launched a strategy for renewable energy that is cantered on diversifying energy sources to transition away from the reality of the oil business and toward a sustainable combination of renewable energy sources. King Abdullah City for Atomic and Renewable Energy collaborated with academic institutions in the Kingdom of Saudi Arabia to obtain more sustainable energy. The private sectors, most notably Saudi Aramco, are mobilized to activate renewable energy sources, with solar energy installations on roofs in the Kingdom as the most noticeable of its efforts. By implementing the Energy Strategy Initiative's operations, the Kingdom will reach its ultimate objective of 58.7 GW of solar and wind energy by the year 2030. Passing through the interim goal for the year 2024 to reach 27.3 GW of renewable energy (Mansour et al., 2019). Overall, the adjustment in the energy structure by reducing oil consumption and increasing the benefits of clean energy (Yasmeen et al., 2020) become part of the mitigating strategies to GHGs emissions.

### 5.3. *Saudi Vision 2030: toward sustainable societies*

Previously, Wogan et al. (2019) examined the Policy Pathways of Saudi Arabia's Contributions to the Paris Agreement in two scenarios; in scenario 1, Saudi Arabia focuses on robust oil export revenues to support a more diversified economy, and in scenario 2, the country emphasizes domestic utilization of oil and gas to accelerate domestic industrialization. The research findings indicate that it is more important for Saudi Arabia to control oil production and transition to renewables instead of pursuing robust oil production. While the aim of robust oil export is to adapt and promote efficiency and renewable energy, it may have some short-term negative consequences on the environment and sustainability. However, in the long term, this approach can lead to increased investment in renewables and efficiency, ultimately contributing towards sustainability and achieving the target of net-zero emissions. Generally, for countries heavily reliant on fossil fuels for investment, robust oil production may seem like the only viable option. However, our research suggests that shifting focus towards renewables and efficiency is essential for long-term sustainability and achieving net-zero emissions. As part of Saudi central bank, vision to reduce $CO_2$ emissions, the first step involves adopting the Circular Carbon Economy (CCE) framework. This entails expediting the comprehensive implementation of the national program for circular carbon economy, which focuses on reducing, reusing, recycling, and removing $CO_2$ emissions (https://www.greeninitiatives.gov.sa). Consequently, this initiative is expected to lead to significant reductions in various sectors, ranging from transportation to building (Hamieh et al., 2022). To support the circular carbon economy national program, it is crucial to prioritize increased recycling of materials such as aluminium, steel, paper, and plastics (IEA,2021). Additionally, strategies promoting materials efficiency need to be adopted across all sectors (Alajmi, 2021). Also (Ata et al., 2023), The materials used in construction and the state of buildings play vital roles in attaining energy efficiency and lowering $CO_2$ emission. These policy measures are essential in ensuring the successful implementation of the circular carbon economy approach.

The second action in line with Saudi Arabia's efforts to reduce $CO_2$ emissions is focused on investing in renewable energy sources. The goal is to shift the current energy mix towards a more sustainable one, with 50 percent of the energy coming from renewables (https://www.greeninitiatives.gov.sa). According to our research findings, this action has the potential to significantly decrease $CO_2$ emissions. Since the electricity and heat sector has the most impact on $CO_2$ emissions, transitioning to renewables can effectively curtail a major source of emissions (Erdogan et al., 2023). To achieve this, the country should electrify various sectors, including transportation, households, and agriculture. Heat pumps will play a crucial role in reducing $CO_2$ emissions in the heat sector. In China, electric heat pumps as opposed to direct electric heating was predicted to reduce yearly electricity consumption by 64.9% in 2060, which also suggest reduction in GHGs emissions (Dong et al., 2023). Besides, investments in the power sector will involve building new renewable energy facilities, upgrading electricity grids (including transmission, distribution, and public electric vehicle chargers), and incorporating battery storage systems (IEA,2021). Energy efficiency investments will be targeted at buildings, industries, and transportation to optimize energy use (Alajmi, 2021). Moreover, other end-use investments should encompass direct utilization of renewables, adoption of electric vehicles, electrification in buildings, industries, and international marine transport, utilization of hydrogen and hydrogen-based fuels (IEA,2021), and the conversion of fossil fuel-based industrial facilities (IEA,2021).

As part of the all-encompassing strategy to cut $CO_2$ emissions, direct air capture (DAC) and carbon capture, utilization, and storage (CCUS) technologies in the industry (IEA,2021) will also be investigated.

As the world's top producer and exporter of clean hydrogen, Saudi Arabia will take the lead in developing a new sustainable energy source as its third step in its goal to cut $CO_2$ emissions. This huge project is thought to be the most potential substitute for fossil fuels. However, because the infrastructure of the country is now entirely reliant on fossil fuels, switching to hydrogen as a primary energy source will need significant investment. As a result, fulfilling all these goals may require some time. Despite the difficulties, this endeavor has important potential outcomes. By spearheading the development of clean hydrogen, Saudi Arabia can significantly reduce its dependency on fossil fuels, which will, in turn, lead to a notable reduction in $CO_2$ emissions (https://www.greeninitiatives.gov.sa).This transition towards a sustainable energy source would mark a crucial step forward in the country's efforts to combat climate change and promote a more environmentally friendly energy landscape (Akinpelu et al., 2023).

The fourth action focuses on increasing energy efficiency by strengthening Saudi Arabia's Energy Efficiency Programs (SEEP) (https://www.greeninitiatives.gov.sa). The success of broad energy transitions relies on garnering support and involvement from all segments of society. Implementing these changes effectively will necessitate widespread social acceptance (IEA,2021). Additionally, reducing $CO_2$ emissions requires changes in behaviour, such as promoting cycling over driving for commuting purposes (IEA,2021). Moreover, the manufacturing and construction sectors must adopt more sustainable materials to effectively curtail $CO_2$ emissions. Energy efficiency measures offer numerous benefits, including emissions reduction, cost savings, and enhanced competitiveness. One example of a successful initiative is the US Department of Energy Better Plants Program (IEA,2021).

The fifth action by KSA focuses on transforming waste management in Riyadh through an ambitious waste management project (https://www.greeninitiatives.gov.sa). According to our research, the waste sector is a significant contributor to $CO_2$ emissions. Therefore, undertaking comprehensive waste management initiatives, will significantly contribute towards mitigating carbon footprint and promoting a more sustainable environment. Overall, based on the research findings, the service variable appears to cause a reduction in $CO_2$ emissions across all sectors in the long term. As a result, it becomes crucial to accelerate energy efficiency efforts in all sectors. By doing so, Saudi Arabia can make significant progress in reducing its carbon footprint while also enjoying the multiple advantages that energy efficiency offers. Although GHG emission in the Kingdom of Saudi Arabia increased, the country is on course to moderate the overall emissions since there already policy apparatus employed to strike a balance between sustainable economic development, environmental protection, and reduction of GHGs emissions.

## 6. Conclusion

Based on a study analyzing greenhouse gas emissions (GHGs) data from various sectors between 1990 and 2020, as well as other relevant variables from 1970 to 2020, the research examines the interaction between $CO_2$ emissions and these studied variables, using econometric model ARDL. The findings reveal that the electricity and heat sector is the largest contributor to GHGs emissions, followed by the transportation sector, and then emissions from the Fugitive sector. Additionally, $CO_2$ emissions in the Kingdom of Saudi Arabia (KSA) are influenced by several factors. Notably, an increase in GDP by 1 percent leads to a 3.46 percent rise in $CO_2$ emissions, a 1 percent increase in agriculture results in a 0.26 percent increase in $CO_2$ emissions, a 1 percent increase in oil production leads to a 4.04 percent increase in $CO_2$ emissions, and a 1 percent increase in the Service sector causes a decrease of 0.79 percent in $CO_2$ emissions. As KSA possesses substantial fossil fuel resources and is among the top 10 countries in $CO_2$ emissions, it is imperative to implement administrative reforms in various sectors, aligning with the Saudi 2030 vision. These findings have significant policy implications for addressing environmental concerns in the country.

Overall, Saudi Arabia has set ambitious goals to reduce $CO_2$ emissions and achieve net-zero emissions by 2060. The implementation of various actions for emission reduction is currently underway and progressing as planned, aimed at meeting these targets. Drawing insights from pioneering countries that have already made progress in their journey towards net-zero emissions can prove beneficial. By studying their experiences, including challenges, successes, and failures, KSA can gain valuable knowledge to guide its own path towards a sustainable and successful transition to net-zero emissions.

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## CRediT authorship contribution statement

**Ahmed Altouma:** Conceptualization, Formal analysis, Writing – original draft. **Bashar Bashir:** Writing – review & editing. **Behnam Ata:** Writing – review & editing. **Akasairi Ocwa:** Writing – review & editing. **Abdullah Alsalman:** Writing – review & editing. **Endre Harsányi:** Visualization, Writing – review & editing. **Safwan Mohammed:** Conceptualization, Formal analysis, Methodology, Writing – original draft.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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