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The impact of air transportation, trade openness, and economic growth on CO_2 emissions in Saudi Arabia

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The global economy has reported an unprecedented increase in growth rates over the last 2 decades, due to rapid evolution in transportation and communications. The rapid growth of international trade has increased the demand for fossil fuel, leading to exacerbated environmental risks. Air transportation is an essential operational practice in trade openness and has many economic benefits. However, its effect on CO_2 emissions is not well understood. Studies on the causal relationships between air transportation, trade openness, economic growth, and CO_2 emissions are lacking, especially across Middle Eastern countries. This study targets Saudi Arabia, one of the largest countries in the Middle East region in terms of economic capabilities and geographical area, to investigate the impact of air transportation, trade openness, and economic growth on CO_2 emissions. To this end, data was derived from the World Development Indicators (WDI) established by the World Bank for the period 1991–2023. An autoregressive, distributed lag autoregressive distributed lag (ARDL) model was used to analyze associations among the study variables; the empirical findings confirm that air transportation, trade openness, and economic growth have positive and statistically significant effects on CO_2 emissions in both long- and short-run scenarios. However, the results illustrate that economic growth alone is unable to sufficiently reduce CO_2 emissions in Saudi Arabia, indicating a lack of connection between economic policies and environmental goals. Thus, these results indicate that the Environmental Kuznets Curve (EKC) hypothesis is not valid for Saudi Arabia. In addition, this study provides useful insights for policymakers to mitigate CO_2 emissions. Suggestions include attracting foreign investment, modifying the structure of trade, mitigating the reliance on imports and enhancing exports, while focusing on green strategies for economic growth, replacing fossil fuels with clean and renewable sources, subsidizing environmentally friendly technologies, and enacting decarbonizing regulations.

KEYWORDS

air transportation, trade openness, economic growth, CO_2 emissions, sustainable development, ARDL model, Saudi Arabia

Abbreviations: CO_2, Carbon dioxide emissions; AT, Air transport; TO, Trade openness; GDP, Economic growth; ARDL, Autoregressive Distributed Lag; ADF, Augmented Dickey -Fuller; PP, Phillips -Perron; KPSS, Kwiatkowski –Phillips –Schmidt –Shin; WDI, World Development Indicators; EKC, Environmental Kuznets Curve.

1 Introduction

In more recent decades, researchers have emphasized the relationship between air transportation, trade openness, economic growth, and CO_2 emissions. Air transportation is one of the key drivers for economic development, since all economies depend on the movement of goods and individuals (Wang et al., 2019). The growth in demand for air transportation is mostly accompanied by higher consumption of fossil fuel (Hao et al., 2020; Talwar et al., 2023). Although most countries have produced green practices to protect the environment and health (Shahzad et al., 2020; Kazemzadeh et al., 2022; Chen et al., 2023), air transportation, which uses fossil fuels, is one of the primary contributors to increasing CO_2 emissions worldwide (Lelieveld et al., 2019). Thus, understanding the dynamic determinants of CO_2 is crucial to achieve an improvement in quality of life and reduce emissions.

Trade openness is the sum of exports and imports as a percentage of GDP (The World Bank, 2022), with numerous researchers using this definition in empirical studies, such as Wang et al. (2024), Frankel and Rose (2005) and Ertugrul et al. (2016). Moreover, although the overall volume of international trade reached 75% in the period 2000–2020 (World Bank, 2023), trade openness is one of the most concerning driving forces for CO_2 emissions (Zhong et al., 2021) due to the expansion of industrialization activities to satisfy demand. Therefore, many researchers have recommended an investigation into the impact of trade openness on CO_2 emissions (e.g., Wiedmann and Lenzen, 2018; Yang et al., 2020).

Economic growth requires increasing the use of natural resources and energy and stimulates production processes which require the use of fossil fuels. Previous research (e.g., Jebli et al., 2016; Anastacio, 2017; Pertiwi et al., 2023; Naseem et al., 2024) has identified the links between economic growth and CO_2 emissions to facilitate existing policies for sustainable economic development. Accordingly, economic growth is one of the key stimulants of trade openness, air transportation, and CO_2 emissions.

Existing academic literature has also confirmed the links between air transportation, trade openness, economic growth, and CO_2 emissions and the fact that, in the Middle East, sustainable development is almost always accompanied by a lack of economic growth and rapid population growth. There are, therefore, substantial challenges related to the environment, economic growth, transportation, and trade in this region, which inevitably hinder institutional capacity in terms of achieving sustainable development fully.

The use of air transportation is continuously increasing as a result of its timeliness. However, the role air transportation plays in influencing CO_2 emissions is still unclear, because of variations in energy efficiency and aviation movement from one country to another (Lo et al., 2020). Hence, this study fills a gap in the current literature by focusing on air transportation in the first instance, but also considering other factors including trade openness and economic growth. Secondly, there is a lack of research on this topic that needs to be addressed (Postorino and Mantecchini, 2014; Larsson et al., 2018; Avotra and Nawaz, 2023), especially across Middle Eastern countries. Thirdly, a search for both specific and casual associations, which will increase comprehension of the current situation of sustainable development by linking air transport, trade openness, and economic growth to CO_2 emissions is essential, and the findings from this study have the potential to extend the literature. Finally, the variables used in this study can be used for a cost-benefit analysis in the context of environmental sustainability, enabling policymakers to better respond to environmental challenges.

This study targets Saudi Arabia, one of the largest countries in the Middle East region in terms of economic capabilities and geographic area, to investigate the impact of air transportation, trade openness, and economic growth on CO_2 emissions, while addressing the following main research question:

To what extent do air transportation, trade openness, and economic growth effect CO_2 emissions?

The fundamental value of this empirical assessment is its contribution to exploring the frontiers of urban policies in environmental sustainability, thus enabling researchers and policymakers to achieve sustainable development goals, as well as providing original, useful insights and perspectives for relevant policy issues in Saudi Arabia.

2 Literature review

Since the 18th century and the onset of the industrial revolution, transportation has been regarded as a precondition for development, though the exact causal relationship hasn't always been conclusively established (Cahill, 2010). Even today, a higher level of income for countries is linked to longer distances traveled annually, although it doesn't necessarily translate to more or less travel time (Cahill, 2010). Aviation has enhanced international trade, thereby increasing income levels. Rising income, growing the specialization in labor division, increasing population growth, and escalating demand for goods, all act to increase the use of air transportation, leading to environmental degradation. Therefore, several researchers have developed models to understand factors affecting CO_2 emissions. For instance, Hasanov et al. (2021) developed a theoretical framework wherein emissions are determined by income, exports, imports, renewable energy, and technological progress. The framework was applied to the BRICS countries using a series of data spanning from 1990 to 2017, taking into account the integration, co-integration, as well as cross-country interdependence and heterogeneity within the panel data.

In 2022 global CO_2 emissions from the transportation increased by more than 250 Mt CO_2 to approximately 8 Gt CO_2, 3% more than in 2021 (International Energy Agency, 2023). Air transportation is considered the main contributor to this increase, in spite of its reduction to roughly 70% during the period of Covide-19 (International Energy Agency, 2023). Although air transport is a major contributor to economic development, it also has several negative consequences for the global environment as one of the largest consumers of fossil fuels. Therefore, researchers have supported linking air transportation with other fields of research, such as the environment, energy use, and the economy (e.g., Balkanski et al., 2010; Baumeister, 2017; Naghawi and Alobeidyeen, 2019). Kongbuamai et al. (2023) examined the effect of air transport and CO_2 emissions on ecological systems between 1992 and 2015 in APEC countries; their findings substantiate that air transport increases CO_2 emissions. Zanjani et al. (2023) have considered the impact of air transport on CO_2 emissions in eight oil-producing countries in the Middle East from 2013 to 2019, investigating both air passengers and air freight to determine the overall influence. Empirical results demonstrate that air passengers have a positive impact on CO_2 emissions in all countries in the study, while air freight has an impact only in Iran and Qatar. Saleem et al. (2018) have examined the impact of a number of variables, including air transport, on CO_2 emissions in Next-11 countries for the period 1975 to 2015; findings concluded that air transport freight has a positive association with GHG emissions, whereas both air and rail passengers had no impact on CO_2 emissions.

On the other hand, other studies have investigated the relationship between air transport and CO_2 emissions from a technical eco-innovation perspective. For example, Chen et al., 2022's findings indicate that air transport is negatively linked to CO_2 emissions and PM2.5 in G-7 countries, highlighting the role of technical structures for aircraft engines in lowering the impact of air transport on air quality. Eco-innovation is the achievement of environmental sustainability using green technologies, such as green energy (Sharif et al., 2019).

In Saudi Arabia, a few studies have examined the relationship between transportation and CO_2 emissions, such as Rahman et al. (2017), Alshehry and Belloumi (2017), Alajmi (2021). However, these studies did not consider air transportation. To address this gap, this study is the first one to examine the impact of air transportation on CO_2 emissions in Saudi Arabia.

The framework developed by Hasanov et al. (2021) theoretically and empirically supports the relationship between international trade and CO_2 emissions. The expansion of international trade resulting from globalization increases environmental degradation. The nexus between trade openness and CO_2 emissions has been discussed widely by many researchers (e.g., Steinberger et al., 2012; Li et al., 2020; Alavijeh et al., 2023; Nwaeze et al., 2023; Omri and Saadaoui, 2023; Wang et al., 2023). However, findings are not consistent across all studies regarding the relationship between trade openness and CO_2 emissions. For example, some studies have found that trade openness increases CO_2 emissions as a result of production processes, based on energy consumption (Sadorsky, 2012). Frankel and Rose (2005) have also tested the impact of trade on CO_2 emissions; findings confirmed a positive impact, unlike other pollutants such as nitrogen dioxide (NO_2) and sulfur dioxide (SO_2). Likewise, Omri and Saadaoui, (2023) found empirically that trade openness has led to an increase in CO_2 emissions for 12 selected MENA countries, while Wang et al. (2023) assessed the effect of trade openness and trade diversification on CO_2 emissions between 1997 and 2019 in 30 countries from the OECD and G20 countries, concluding that trade openness increases CO_2 emissions, while trade diversification reduces CO_2 emissions. Furthermore, Ansari et al. (2020) examined a number of countries (including the United States, Canada, Japan, Saudi Arabia and Iran); findings confirmed that trade openness increases CO_2 emissions.

In contrast, findings from other studies have suggested that trade openness reduces CO_2 emissions. For example, Hasanov et al. (2018) examined the impact of exports and imports on CO_2 emissions in nine major exporting countries; empirical findings determined there is a negative association between exports, imports, and CO_2 emissions. Likewise, Al-Mulali et al. (2015) examined the effect of trade openness on pollution levels in 23 European countries from 1990 to 2013. Study findings concurred with the previous example; that is, increased trade openness leads to a decrease in CO_2 emissions. These findings emphasize the role of trade openness as a valuable strategy in preserving the environment. Al Mamun et al. (2014) investigated 136 countries between 1980 and 2009, examining the relationship between trade openness and CO_2 emissions. Countries were divided into three categories, based on income level; findings established that trade openness has a negative impact on CO_2 emissions in countries of three groups. Sohag et al. (2017) examined the effect of trade openness, among other variables, on CO_2 emissions for 82 middle-income countries during the period 1980–2012. They found that trade openness leads to decreased CO_2 emissions in the high to middle income countries.

The relationship between trade openness and CO_2 emissions has been widely examined. Extensive empirical studies exist for the pollution-economic growth nexus, although they exhibit inconsistent findings (e.g., Gao and Zhang, 2014; Mikayilov et al., 2018; Nosheen et al., 2021; Genç et al., 2022). In this context, the environmental Kuznets curve (EKC) is the most dominant hypothesis which examines the nexus between environmental deterioration and income (Narayan and Narayan, 2010). Raggad (2018) examined the relationship between a set of variables, including economic growth and CO_2 emissions in Saudi Arabia for the period from 1971 to 2014. The study determined that the association between economic growth and CO_2 emissions is positive in both the short- and the long-run. Iqbal et al. (2023) examined the effects of several factors on CO_2 emissions, including economic growth, in BRICS countries between 2000 and 2018; findings indicated that increases in economic growth led to an increase in CO_2 emissions in BRICS economies.

In the context of Saudi Arabia, studies on the relationship between trade openness and CO_2 emissions are limited. Daly and Abdouli (2023) examined the relationship between CO_2 emissions and trade openness for the period 1990–2017. They found a positive bidirectional causal relationship between CO_2 emissions and trade openness, indicating that Saudi Arabia supports trade without considering environmental quality. Belloumi and Alshehry (2020) examined the relationship between trade openness and environmental quality for the period 1971–2016. Their study revealed that trade openness increases CO_2 emissions in the long-term. Our study examines the impact of trade openness on CO_2 emissions in Saudi Arabia for three reasons. Firstly, there is a scarcity of studies that considered the impact of trade openness on CO_2 emissions. Secondly, Saudi Arabia, as a wealthy nation, has a large volume of international trade, requiring the assessment of relationship between trade openness and environmental quality. Lastly, our study extends time range, as this covers the period from 1991 to 2023.

The environmental Kuznets curve (EKC) hypothesis, based on an inverted U-shaped, has linked economic growth to the environmental degradation (Dinda and Coondoo, 2006; Akbostancı et al., 2009; Lee and Lee, 2009). Based on EKC hypothesis many researchers have examined the causal associations between economic growth and CO_2 emissions, and they provided contradicting results. For instance, Adzawla et al., 2019; Kasperowicz 2015; Arouri et al., 2012 confirm it, while others Hasanov et al., 2019; Raggad, 2018; Aye et al., 2017; Abid 2016 did not confirm it.

TABLE 1 Study variables.

Variables	Measurement	Source
Air transport (AT)	Passengers carried	WDI
Trade openness (TO)	Percentage of GDP	WDI
Economic growth (GDP)	GDP *per capita* (constant: 2015 US$)	WDI
Carbon dioxide emissions (CO_2)	CO_2 emissions (metric tons *per capita*)	WDI

Several studies, concerning Saudi Arabia have examined the effect of economic growth on CO_2 emissions, such as AlNemer et al. (2023), Raggad, (2020), Agboola et al. (2021), Alshehry and Belloumi, (2015), Alkhathlan and Javid (2013), and Raggad, (2018). All these studies have concluded that economic growth increases CO_2 emissions. However, these empirical works primarily assessed the effect of economic growth on CO_2 emissions using other variables, such as energy consumption, without considering transportation and trade openness. With enormous economic capabilities, such as GDP that equals 1.11 trillion USD (WDI, 2023), Saudi Arabia has experienced rapid growth in its transportation and trade sectors. Total CO_2 emissions measured at 14.26 metric tons *per capita* in 2020 (WDI, 2023) contribute to increased environmental hazards. Therefore, it is important to examine the impact of economic growth on CO_2 emissions in the context of air transportation and trade openness.

In the context of Saudi Arabia, no previous study has integrated the variables used in this study, emphasizing the significance of our empirical investigation in exploring variables that have not been assessed before. Consequently, this study has the potential to provide valuable insights for researchers and policymakers.

Worldwide, the current literature on the relationship between air transportation, trade openness, economic growth, and CO_2 emissions is not consistent, with contradictory findings established by studies in both similar and different regions, implying the level of influence can vary from one country to another, and from one time to another. A large part of the literature demonstrates that this disagreement refers to differences in data and methodologies. Other studies found that the nexus between transportation, trade openness, the economy, and CO_2 emissions is complex. However, the main gap in the literature is the failure to consider differences in transportation modes (i.e., air, road, rail, and sea), as the impact of each mode on CO_2 emissions can vary considerably. Providing empirical results at a detailed level enhances the existing literature and increases knowledge. In general, studies on the impact of air transportation on CO_2 emissions are very limited, and no previous studies on this variable which focus specifically on the context of Saudi Arabia exist. Hence, this study, which empirically considers air transportation with the variables trade openness and economic growth on CO_2 emissions has made a profound difference to knowledge in this field.

3 Data and methods

This study examines the impact of air transportation, trade openness, and economic growth on CO_2 emissions. Data for this study is derived from the World Development Indicators (WDI) developed by the World Bank, covering the period 1990–2023. The WDI do not provide data for Saudi Arabia on some variables, such as CO_2 emissions, prior to 1990. Table 1 presents the study variables and how they are measured. These variables are widely used by researchers such as Al-Mulali et al. (2015), Avotra & Nawaz, (2023), Ansari et al. (2020), Arouri et al. (2012), Azlina et al. (2017), Ertugrul et al. (2016) and Habib et al. (2022).

We used the econometric software Stata 17.0 in our study. The study utilizes an autoregressive distributed lag (ARDL) model specification to examine the nexus between air transport, GDP *per capita*, and CO_2 emissions, as outlined in Formula 1 below, based on Narayan and Narayan (2010). The ARDL model gives realistic and efficient estimates with a mixed order of stationarity of the variables for long-run cointegration test (Pesaran et al., 1996). The ARDL model does not require the variables to possess identical orders of integration. Instead, it considers variables with either 1 order or 0 integration (Pesaran et al., 2001). This study follows other researchers who have used the ARDL to determine factors affecting environmental degradation (e.g., Li et al., 2017; Koengkan, 2018; Shafique et al., 2021).

$$CO_{2t} = f\ (AT_t, TO_t, GDP_t) \quad (1)$$

Where CO_{2t} is a proxy for carbon emissions (metric tons *per capita*), AT_t represents air transport and passengers carried, TO_t denotes trade as a percentage of GDP, and GDP_t refers to GDP *per capita* (constant: 2015 US$).

The same variables can also be expressed as natural logarithms using Formula 2:

$$\mathrm{Ln}\ (CO_2) = \beta 0 + \beta 1\ \mathrm{Ln}\,(AT_t) + \beta 2 \times \mathrm{Ln}\,(TO_t) + \beta 3 \times \mathrm{Ln}\,(GDP_t) + e_t \quad (2)$$

Where Ln represents the natural logarithm, β_i (i = 1, . . . , 4) refers to the parameters of the model, and e_t represents the error term.

The study employed the Augmented Dickey–Fuller (ADF) test, Phillips–Perron (PP) test, and Kwiatkowski-Phillips-Schmidt-Shin test (KPSS) to assess stationarity. According to Pesaran et al. (2001) long-run, causal relationships between variables can be computed using ordinary least squares (OLS). Specifying cointegration between variables can be estimated using OLS, a conditional unrestricted error correction model. Formula 3 is based on Pesaran et al.'s (2001) formula for ARDL, as follows:

$$Y_t = \gamma^{oi} + \sum\nolimits_{(i=1)}^{P} \delta_i\, Y_{t-I} + \sum\nolimits_{(i=0)}^{q} \beta_i\, X_{t-I} + e_{it} \quad (3)$$

Where Y_t is a vector and the variables in (X_t) refer to I (0) and I (1), β and δ are proxies for coefficients; γ denotes the constant, I = 1, . . ., k; p and q are proxies for optimal lag orders; e_{it} represents error term.

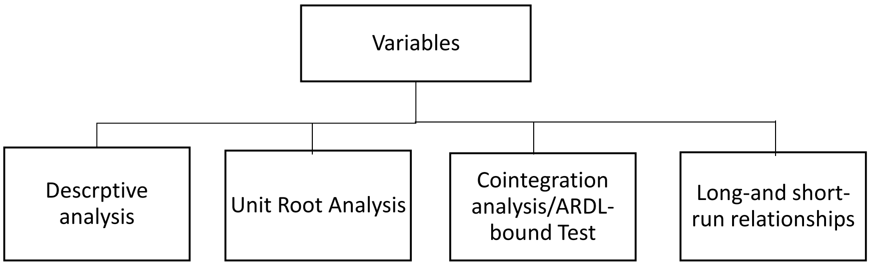

FIGURE 1
Methodological producers.

TABLE 2 Descriptive statistics for study variables.

Variables	Mean	Min	Max	S.D.
GDP *per capita* (constant: 2015 US$)	20,960.66	13,249.18	35,689.59	6,034.782
CO_2 emissions (metric tons *per capita*)	13.35095295	10.70951816	17.25779307	2.090843931
Air transport, passengers carried	14,769,088.79	51,36,000	46,181,487	10,505,714
Trade (% of GDP)	75.18343	49.71347	120.6195	13.26286

It should be noted that I (0) pertains to the lower bound, while I (1) refers to upper bound. If the calculated F value exceeds the value of the upper critical bound, this means that the variables are cointegrated. However, if the F value falls below the lower critical bound, this means there is no cointegration between the variables. On the other hand, if the F value ranges between the upper and lower critical bounds, the results are inconclusive.

Formula 4 can be utilized to illustrate the ARDL model for cases of cointegration, as proposed by Pesaran et al. (2001).

$$Y_t = \gamma^{oi} + \sum\nolimits_{(i=1)}^{P} \delta_{\mathrm{i}} \mathrm{Y}_{\mathrm{t-I}} + \sum\nolimits_{(i=1)}^{P} \beta_{\mathrm{i}} \mathrm{X}_{\mathrm{t-I}} + \lambda \mathrm{ECT} + \mathrm{e}_{\mathrm{it}} \tag{4}$$

In line with the ARDL model, diagnostic tests such as functional form, normality, heteroscedasticity, and serial correlation were used to check stationary criteria. Stability was assessed using CUSUM and CUSUMSQ tests.

Figure 1 summarizes the procedural steps of this study.

4 Empirical results

4.1 Descriptive statistics

Table 2 provides descriptive statistics for study variables. The average GDP *per capita* is relatively high, and there were relatively high fluctuations in CO_2 emissions over the duration of the study. With regards to air transport, the number of passengers carried also increased over the period 1990–2023; the minimum number was 5136000 and the maximum 46181487 passengers. These results establish the existence of a quantum leap in economic development, as trade has likewise increased substantially, from 49.71 to 120.619 of GDP.

TABLE 3 Stationarity results from the three tests conducted for the study.

	ADF	PP	KPSS	ADF	PP	KPSS
	Level			First difference		
CO_2	−2.956	−3.576	0.947	−7.867**	−7.228**	0.334*
Air transport	−1.873	−3.426	0.938	−5.324**	−5.042**	0.349*
Trade openness	−1.674	−1.542	0.935	−3.316**	−3.171**	0.421*
GDP	−2.745	−2.012	0.944	−5.218**	−5.107**	0.362*

**Is a significant level of 0.01, and * is a significant level of 0.05.

4.2 Results from the unit root analysis

Table 3 illustrates the results of the Augmented Dickey-Fuller (ADF) test, Phillips-Perron (PP) test, and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test for stationarity. The empirical findings illustrate that CO_2 emissions, air transport, trade openness, and GDP, are all non-stationary I (0) and the results of the first difference are all stationary I (1).

4.3 Results from the cointegration analysis

A co-integration test assesses the existence of a long-term relationship among multiple time series. It is employed to pinpoint situations where two or more non-stationary time series are co-integrated; that is, they are integrated together in such a manner that they cannot deviate from equilibrium over an extended period.

To compute the long-run relationship between the variables with respect to the third formula, the F test was used. The F value is a measure of how much the variables in the ARDL model are cointegrated with each other. For a model to be considered

TABLE 4 ARDL-bound test.

$CO_{2t} = f\ (AT_t, TO_t, GDP_t)$		
F value (%)	9.58	
Critical value bounds (%)		
Sig (%)	Lower bounds	Upper bounds
1	2.786	4.01
5	3.426	4.895
10	4.871	6.753

TABLE 5 Lagged selection Criteria.

Lag	Lag L	AIC
0	−554.0845	48.18082
1	−476.4521	42.37887
2	−468.6344	42.46002

TABLE 6 Long-run elasticities.

Variables	Coefficients	Std. error	t statistic	Prob
ART	0.358	0.162	2.209	0.003
TRD	0.396	0.158	2.506	0.007
GDP	0.405	0.144	2.813	0.004
C	6.687	2.137	3.129	0.012

TABLE 7 Short-run elasticities.

Variables	Coefficients	Std. error	t statistic	Prob
$\Delta LCO_2\ (-1)$	0.258	0.102	2.530	0.012
ΔL ART	0.872	0.124	7.032	0.000
ΔL ART (−1)	0.429	0.157	2.732	0.035
ΔL TRD	0.652	0.128	5.094	0.000
ΔL TRD (−1)	0.397	0.134	2.963	0.041
ΔL GDP	0.558	0.162	3.444	0.000
ΔL GDP (−1)	0.322	0.115	2.800	0.050
ECM (−1)	0.717	0.127	5.646	0.000

TABLE 8 Outcomes of diagnostic tests.

Diagnostic tests	
Functional form	0.85 (0.44)
Serial correlation	2.61 (0.03)
Heteroscedasticity	0.77 (0.54)
Normality	3.68 (0.11)

successful, it should have a high F value (at least higher than one); as can be seen from Table 4, the F value is 9.58, based on the bounds test, which is significant ($p < 0.01$). This result implies an existing long-run relationship between CO_2 emissions, air transport, trade openness, and GDP *per capita*, with a significance level of 1%.

Based on the cointegration relationship between the investigated variables, as illustrated in Table 4, the ARDL model can be applied to compute the coefficients from Formula 3, with a lag of 2. Various criteria exist for determining the number of lags, with the Akaike Information Criteria (AIC) and Schwarz Bayesian Criteria (SIC) (Anderson and Burnham, 2002) being the most renowned. A preference for AIC over SIC can be observed due to three key reasons: firstly, AIC is grounded in information theory principles, unlike SIC. Secondly, there are debatable hypotheses concerning the derivation of SIC. Lastly, empirical studies indicate that AIC tends to be more efficient than SIC. As outlined in Table 5 below, applying AIC directly to the variables led to the identification of two lags.

Tables 6, 7 illustrate the long- and short-run relationships among the study variables, and indicates that an increase in air transport, trade, and economic growth would be associated with a similar increase in CO_2 emissions in both long- and short-run scenarios. That is, in the long-run, a 1% increase in air transport will increase CO_2 emissions by 0.358%, a 1% increase in trade will increase CO_2 emissions 0.396%, and a 1% increase in GDP will increase CO_2 emissions by 0.405%. Similarly, in the short-run, a 1% increase in air transport will increase CO_2 emissions by 0.872%, a 1% increase in trade will increase CO_2 emissions 0.652%, and a 1% increase in economic growth will increase CO_2 emissions by 0.558%.

Tables 6, 7 also demonstrate that coefficients of short-run variables are greater than those for the long-run. Furthermore, study results reveal the non-existence of an inverted U-shaped relationship between CO_2 emissions and air transport, trade openness, and GDP, as these variables have a positive impact on CO_2 emissions in both the short- and long-run.

Finally, Table 8 presents the outcomes of diagnostic tests, including serial correlation, functional form, normality, and heteroscedasticity, and demonstrate that the ARDL model has successfully passed all the tests. The CUSUM and CUSUMSQ tests established that the model is stable. When considering serial correlation, at the 1% significance level, the null hypothesis of no serial correlation in the residuals cannot be rejected, although it can be rejected at 5% and 10% levels.

5 Discussion

Climate change is one of the most important challenges the world is facing at the moment. Saudi Arabia has achieved real progress towards sustainable development, smart cities, and economic development, aiming to create a balance in social, economic, and environmental pillars of sustainability. Therefore, it is important to investigate factors affecting CO_2 emissions, in order to reduce environmental challenges.

Empirical results imply that air transport, trade, and economic growth all stimulate CO_2 emissions, leading to environmental degradation in both the long- and short-run. The results suggest that economic growth and trade openness are unable to reduce CO_2 emissions in Saudi Arabia. The results reveal that the EKC hypothesis is not valid for Saudi Arabia.

These observations do not align with the conclusions of Kharbach and Chfadi (2017), who have speculated on the validity of the transport EKC in Morocco, or with the findings of Rasool et al. (2019), which indicate that an augmentation of economic growth leads to a reduction in CO_2 emissions, which they attribute to advancements in transportation technology. On the other hand, this study's findings do align with the research conducted by Azlina et al. (2014), in Malaysia, Mohsin et al. (2019) in Pakistan, and Ben Abdallah et al. (2013) in Tunisia.

Seemingly, when trade openness increases, it contributes to economic growth; however, it also raises demand for air transportation, thereby increasing CO_2 emissions. Therefore, air transportation causes increased CO_2 emissions. This result is in agreement with the findings of Paç and Öner (2023), and Avorta and Nawaz (2023), who established that the impact of air transportation on CO_2 emissions is positive. Similarly, Habib et al. (2022) found that air transportation had a positive effect on CO_2 emissions in G20 countries between 1990 and 2016.

The empirical findings of this study indicate that CO_2 emissions are increased by trade openness. However, there is no confirmed link between these two variables, as studies in the academic literature have reported a range of conflicting results. The results of this study agree with those of Ansari et al. (2020), who investigated a set of countries which are considered to produce the highest rates of CO_2, including Canada, Japan, the United States, Saudi Arabia, and Iran. Both studies conclude that an increase in trade results in an increase in CO_2 emissions. Belloumi and Alshehry (2020) found that trade openness increases CO_2 emissions in Saudi Arabia. Likewise, Rasiah et al. (2018) found that trade openness has increased CO_2 emissions in selected ASEAN countries. Similarly, Tamazian and Rao (2010) tested 24 transition countries between 1993 and 2004; findings correlated with those above, that trade openness increases CO_2 emissions. In contrast, Omri, (2013) found that trade openness had a negative influence on CO_2 emissions in individual MENA countries between 1990 and 2011. Likewise, Al Mamun et al. (2014) examined the link between CO_2 emissions and trade openness in 136 countries; findings indicated that the impact of trade openness on CO_2 emissions is negative for most countries in the study.

Increased CO_2 emissions are related to an increase in international trade, which requires higher rates of energy use. As trade improves economic growth, reducing CO_2 emissions becomes a priority, as discussed by Sebri and Ben-Salha (2014). Furthermore, CO_2 emissions are influenced by the level of imports and exports; an increase in imports leads to an increase in CO_2 emissions. Hence, as the Saudi Arabian economy has a high level of imports, for both capital formation and consumer goods, it is reasonable to assert that trade openness has a positive impact on CO_2 emissions.

The empirical results of this study indicate that economic growth has a positive and statistically significant impact on CO_2 emissions. These results are consistent with other researchers, such as Sari and Soytas (2009), who examined the nexus between CO_2 emissions, economic growth, energy use and total employment in five countries: Saudi Arabia, Indonesia, Algeria, Nigeria, and Venezuela between 1971 and 2002. Study findings could confirm a positive association among these variables only for Saudi Arabia. These empirical results correspond to those of Aye et al. (2017) who found that economic growth has a positive effect on CO_2 emission in high growth countries, but a negative effect in low growth, developing countries. Similarly, Raggad (2018) empirically found that economic growth has a positive effect on CO_2 emissions in Saudi Arabia. From an environmental viewpoint, time series analysis indicates that the relationship between GDP *per capita* and CO_2 emissions does not align with a sustainable path in Saudi Arabia. Therefore, it is important to reassess economic growth strategies, emphasizing the broader ramifications of economic growth on environmental sustainability.

6 Conclusion and policy implications

The current study is based on data collected between 1990 and 2023; it examines the impact of air transportation, trade openness, and economic growth on CO_2 emissions in Saudi Arabia, using an ARDL model. To achieve this objective, several methodological procedures were employed, including data, sample, descriptive statistics, unit root analysis, cointegration analysis, the ARDL-bound test, and long-and short-run relationships.

The central question of this study is the extent to which air transportation, trade openness, and economic growth impact on CO_2 emissions. Empirical results reveal that air transportation, trade openness, and economic growth have a positive and statistically significant impact on CO_2 emissions in both the long- and short-run in Saudi Arabia. These findings are extensively supported and explored by the literature, as shown in the previous section. The inability of economic growth to reduce CO_2 emissions may perhaps be related to the reliance of Saudi Arabia on its non-renewable energy sources to enhance economic development. Thus, economic growth will increase CO_2 emissions. This clarification is widely supported and examined by other studies in the literature, and this empirical study has proved that economic growth has increased environmental degradation in Saudi Arabia. Additionally, trade openness does not operate in a vacuum; rather, it associates with transportation and economic drivers. Therefore, positive long-run coefficients of trade openness and air transportation support the assertion that trade and air transportation stimulate economic growth, increasing CO_2 emissions. These findings are in alignment with prior studies linking globalization, economic complexity, and trade to CO_2 emissions, such as Koengkan et al. (2020), Kazemzadeh et al. (2022); and other studies which link air transportation and economic growth to CO_2 emissions, such as Avorta and Nawaz (2023) and Paç and Öner (2023).

The empirical findings have determined that the EKC hypothesis is not valid for Saudi Arabia. This result indicates a lack of connection between economic policies and environmental goals. The new insight is that the relationship between high income and the environment does not raise the demand for environmental protection if not accompanied by efficient economic-environmental policies. It is necessary for policymakers in Saudi Arabia to achieve economic development by appropriate instruments in terms of environmental hazards. In this way, raising the efficiency in the use of resources and adopting instruments which encourage people to use renewable energies should be at the core of Saudi Arabian agenda (Taher and Hajjar, 2014; Samargandi, 2017; Raggad, 2018).

Study findings suggest that trade policies are not designed effectively, and so do not incentivize businesses to adopt green practices, such as emissions trading systems or imposing high taxes on goods with high CO_2 emissions. Despite Saudi Arabia's noticeable desire to seek alternative income sources, its economy is still reliant on oil reserves, which allows a continual increase in imports, which in turn leads to an increased demand for air transportation. Hence, linking trade policies to environmental goals in an effective manner can reduce CO_2 emissions (Ansari et al., 2020).

Based on the conclusions above, the question arises: What are the primary policy implications of this study? Firstly, a focus on attracting foreign investment is a strategic and environmental priority. In addition, an influx of foreign investment to introduce clean technologies would have a spillover influence, by increasing industrialization operations, protecting the environment, and mitigating the effects of CO_2 and other pollutants.

Alternatively, modifying the structure of trade could help to lower CO_2 emissions. The current economic structure is, for the most part, dependent on imports which do not provide real value in terms of low carbon strategies. Thus, a focus on local, exportable industries would both reduce imports and mitigate CO_2 emissions. On the other hand, an increase in imports could provide opportunities for growth returns on investment, technical support, country competitiveness, and improvements for a sustainable environment. Therefore, modifying the trade structure requires a reassessment of the manufacturing structure to reduce secondary industries, and shift production away from methods requiring high energy usage, thereby causing high level emissions, to more sustainable, environmentally friendly methods, using natural power sources.

Environmental practices should focus on green strategies for economic growth, which seek to optimize the use of clean energy, thereby reducing the use of fossil fuels. Replacing fossil fuels with clean, renewable sources such as solar and wind, subsidizing environmentally friendly technologies, and enacting decarbonizing regulations could effectively reduce CO_2 emissions.

Finally, it should be noted that the success of the policy implications detailed above requires activating cooperation channels between public sector authorities, encouraging public participation, and establishing a legislative framework to ensure sustainable development.

7 Limitations and future research

A major drawback of this study is that it is limited to one mode of transportation, due to a lack of data for other methods, and thus trade has been used as a percentage of the GDP to obtain more realistic results. Therefore, future research could examine other modes of transportation, such as road, sea, and rail. Considering an increase in these transportation modes could perhaps support economic growth in Saudi Arabia. This study provides a basis for comparative research in the context of Middle Eastern countries and high income countries; thus, future research should be built on these empirical findings.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

AA: Writing–original draft, Writing–review and editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1366054/full#supplementary-material

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