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Full Length Article

Saudi Arabia's path to carbon neutrality: Analysis of the role of Hajj pilgrimage, energy consumption, and economic growth

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ABSTRACT

Saudi Arabia's religious sites stimulate economic growth and create green jobs through sustainable tourism. Tourism expansion may raise carbon dioxide (CO_2) emissions due to energy use. Thus, this article examines 1970–2019 time series data to assess how Hajj pilgrims, energy consumption, and economic growth affect Saudi Arabia's CO_2 emissions. Unit root tests analyzed data stationarity, while the autoregressive distributed lag (ARDL) method investigated the variable nexus in the near and distant futures. A 1% boost in Hajj pilgrims and energy usage would raise CO_2 emissions by 0.02% and 0.91% in the near term and 0.03% and 1.02% in the long term. By redeploying money into big carbon abatement projects, a 1% economic expansion reduces CO_2 emissions by 0.04% in the near term and 0.05% in the long term. Multiple estimators, including the fully modified least squares (FMOLS), dynamic ordinary least squares (DOLS), and canonical cointegrating regression (CCR), were utilized to test the robustness of ARDL results. Pairwise Granger causality study analyzed the components' causal relationship. This article proposes Saudi Arabian carbon neutrality and green pilgrimage policies.

1. Introduction

The ongoing issue of greenhouse gases (GHGs), explicitly CO_2 emissions, resulting from fossil fuel operation and deforestation, has led to a growing apprehension about climate change and global warming in the twenty-first period (IPCC, 2023). Carbon emissions have doubled since the 1960s, causing the majority of environmental issues (Jones et al., 2023). Environmental degradation has increasingly garnered global attention due to growing awareness of its severe consequences. The need to achieve sustainable development, reduce emissions, and achieve carbon neutrality has become increasingly important (Zhang et al., 2022). Approximately 140 regions agreed to shift to carbon-free by either 2050 or 2060 as of November 2022 (Climate Action Tracker, 2023).

The transport segment is the leading generator of CO_2 pollution due to the heightened energy consumption related to travel and tourism (Irfan et al., 2023). The tourism business has been a foremost contributor to GDP expansion in developed as well as emerging nations over the past forty years, playing a pointed function in the globe's economic evolution (Wijesekara et al., 2022). This sector was a major influencer on worldwide employment growth, accounting for 20% of all newfound global employment from 2014 to 2019, beforehand the COVID-19 pandemic. In 2019, this activity represented 10.3% of the workforce (334 million jobs) and added 10.4% to the worldwide GDP (US$ 10 trillion). They maintained a substantial impact of 7.6% on the worldwide GDP (WTTC, 2023) despite the impact of the epidemic. Travel services, including hotel, lodging, and catering sectors, create job openings that help reduce unemployment levels and promote expansion in both the services and manufacturing industries. These contributions have a substantial impact on the economies of developed and emerging economies (Khizar et al., 2023).

Tourism in Saudi Arabia primarily revolves around religious pilgrimages, specifically the Hajj, which attracts millions of Muslims worldwide (Kouchi et al., 2018). Saudi Arabia attracted more than 20 million tourists in 2019 (World Bank, 2023), making it the second-largest attraction for tourists in the Middle East. Religious tourism is a significant revenue source in Saudi Arabia, alongside oil exports. In 2019, Saudi Arabia's tourism segment contributed 8.3% to the Kingdom's overall GDP and employed 1.3 million individuals. Saudi Arabia's tourism sector is projected to experience an annual growth proportion of 11% in the next ten years, positioning it as the quickest-rising tourism commerce in the Middle East and North Africa (MENA) (WTTC, 2022). The Saudi Arabian government has implemented new tourism infrastructure to enhance the

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diversity of the country and cater to the needs of both religious and non-religious tourists. This has resulted in an increased demand for Hajj tourism. The adoption of Hajj tourism is intended to support the country's goal of increasing visitor numbers from 17 million to 30 million by 2025. The Saudi Vision 2030 endeavors are driving innovation and technological advancements in Saudi Arabia, which in turn is boosting the country's market share in Hajj tourism. The tourism industry's GDP contribution is projected to reach approximately US$ 170 billion by 2032, accounting for 17.1% of the overall economy (WTTC, 2022). Tourism employment has the potential to increase twofold in the next decade, resulting in the creation of over 1.4 million jobs. This growth is projected to lead to nearly three million individuals employed in the tourism sector by the year 2032. The employment projections and the segment's influence on the Kingdom's GDP exceed the aspirations defined by the authority's Vision 2030 tactical outline.

While the economic benefits of increased tourism are clear, it is decisive to admit the impending environmental concerns. Adebayo et al. (2023) found that tourists influence the emission level through their usage of energy for lodging, transport, and recreational activities. The tourism industry's significant energy consumption directly contributes to temperature rise via CO_2 pollution (Nwaeze et al., 2023). Tourism is liable for over 5% of emissions worldwide. The transport segment accounts for 75% of the emissions, while accommodation facilities contribute 20% to the overall total (Jiaqi et al., 2022). The link concerning household energy consumption, excluding economic with transport pursuits, underscores the interrelationship involving the rise of travel agencies and CO_2 emissions. Worries have been raised about the harmful effects of excessive energy utilization in the tourism sphere.

The World Tourism Organization (UNWTO, 2024) acknowledges tourism as a key driver for improving the management of the environment, transport networks, and overall structure. These enhancements boost the economic progression in developed and developing countries. Several countries have implemented ecological tax schemes and imposed tariffs on tourism activities to generate resources for mitigating the harmful impacts of tourism and protecting the environment. Environmental protection, community development, and poverty alleviation are all possible outcomes of sustainable tourism in different destinations (Baloch et al., 2023). The 2030 Sustainable Development Goals (SDGs) include several mentions of tourism. SDG Target 8.9 specifically aims to foster sustainable tourism that designs employment and supports the conservation of regional customs and goods. SDG Target 12. b illustrates the significance of observing the developmental consequences of green tourism, specifically sustainable manufacturing and usage. SDG Target 14.7 seeks to promote financial benefits for emerging countries by sustainably utilizing natural resources involving tourism. Tourism has the potential to influence all other SDGs. Following poverty reduction, tourism plays a vital role in creating employment and generating revenue. Research on sustainability views in tourism is crucial for countries like Saudi Arabia, which heavily depend on tourism for economic growth. The UNWTO has expressed appreciation for religion-based tourism as a means of safeguarding humanity's collective heritage and fostering cultural comprehension. Nevertheless, there are notable challenges that need to be resolved to achieve these benefits. The challenges involve conserving sacred places, protecting regional traditions and religious practices, and promoting the welfare of local populations (Elgammal & Alhothali, 2021).

There is growing interest among researchers in studying the interconnectedness involving tourism, energy use, economic development, and ecological sustainability. Numerous scholars have explored the connection between tourism, economy, energy, and pollutants across various zones. Tourism possesses both beneficial and disastrous impressions on the natural world of a particular area (Raihan, 2024). Existing research has offered a theoretical understanding of the connection linking tourism with air quality and ecological degradation. However, more is needed about the particular effects of traveling on the release of CO_2. There has been a scarcity of research conducted on the environmental ramifications of tourism in developing countries like Saudi Arabia (Hassan et al., 2022). While multiple papers have assessed the economic dimensions of the Hajj pilgrimage (Kouchi et al., 2018), there has been limited focus on the environmental consequences of the pilgrimage in Saudi Arabia, specifically concerning the use of econometric approaches. These studies are cardinal for informing the extension of sustainable tourism and green pilgrimage strategies in Saudi Arabia. There is an exit of a research deficiency in comprehension of the link between the Hajj pilgrimage and CO_2 emissions, particularly in achieving zero emissions and attaining the SDGs. This investigation seeks to analyze the influence of Hajj pilgrims' arrivals, GDP expansion, and energy utilization on CO_2 pollution in Saudi Arabia by analyzing annual data from 1970 to 2019 to address the existing research gap.

The selection of Saudi Arabia is motivated by various factors that make it an interesting and relevant area for research. Saudi Arabia has underwent pointed economic expansion in contemporary ages, which has elevated its global prominence (Ali et al., 2023). In 2022, the Kingdom had an economy of USD 1.11 trillion and a GDP per capita of USD 30,436, making it the most prosperous region in the MENA (World Bank, 2023). Economic rapid progress is frequently simultaneous to a sizable growth in CO_2 emissions resulting from energy consumption, leading to significant environmental consequences. In 2021, Saudi Arabia's energy consumption was primarily composed of 47% natural gas and 53% crude oil, along with other petroleum liquids (EIA, 2023). Saudi Arabia holds the second-biggest oil and the fifth-biggest natural gas holders in the Earth. The global oil reserves account for 15.6% of the total, while natural gas reserves account for 4.4%. Saudi Arabia is the foremost global oil exporter, with a daily export volume of 6.6 million barrels in 2020. It also ranks among the top oil producers, with a daily production of 9.2 million barrels in 2020. The Saudi Arabian economy heavily relies on petroleum, with oil constituting 90% of the country's exports and almost 75% of the government's revenue. The Kingdom's domestic oil consumption has consistently risen, currently accounting for approximately 25% of its total oil production. Saudi Arabia ranks as the 16th largest global consumer of energy and exhibits the most rapid growth in energy utilization among Middle Eastern countries. Saudi Arabia's CO_2 emissions from fossil fuels alongside manufacturing operations in 2022 amounted to approximately 608 million tons (EIA, 2023).

Saudi Arabia acknowledges the significance and potential of tourism as a major contributor to the economy and a significant job creator (Mir & Kulibi, 2023). The tourism segment is identified as a significant strategic business for development in Vision 2030. In December 2022, the Ministry of Tourism implemented ten regulations aimed at advancing the tourism sector in alignment with Saudi Arabia's post-COVID-19 revival. Saudi Arabia's government strategies and efforts have led to positive outcomes, with the country being ranked as the globe's second-most rapidly expanding tourism hotspot in 2022 (Mir & Kulibi, 2023). The Kingdom is ranked 13th globally in terms of global tourist arrivals in 2022. Saudi Arabia's high per capita consumption of energy poses challenges for reducing emissions while maintaining economic growth. Saudi Arabia has made significant progress in reducing carbon emissions and establishing itself as an example of sustainability (Yusuf & Lytras, 2023). The country has established ambitious goals to achieve carbon neutrality by 2060 and is making significant progress towards its attainment. The implementation of appropriate actions and regulations is crucial for achieving climate goals and ensuring environmental sustainability. Developing a suitable model to probe the nexus amid Hajj pilgrimage, energy use, economic rise, and CO_2 release in Saudi Arabia can provide valuable insights for implementing effective policies to cut emissions and achieve climate goals. This can also contribute to the nation's economy by promoting energy conservation, sustainable tourism, and green pilgrimage practices.

This probe explored the consequences of the Hajj pilgrimage, energy usage, and GDP growth on CO_2 emissions, contributing to the prevailing comprehension of this topic. The novelty of this investigation is that it explored the link between the Hajj pilgrimage and CO_2 emissions, aiming to offer empirical evidence on the ecological effects of religious tourism. This study employed a dataset spanning five decades (1970–2019) to apply an ARDL simulation. The devotion of the model was to gauge the long and intermediate consequences of Hajj pilgrimage, GDP extension, and energy utilization on CO_2 emissions. In addition, various statistical tests such as unit root evaluations, cointegration regression approaches, and diagnostic assessments were adopted to evaluate the accuracy of the ARDL conclusions. The pairwise Granger examination for causality was applied to uncover the causal link involving the factors. This study highlights the implications of promoting green energy, energy-efficient technologies, and funding cleaner energy technologies in the circumstances of pilgrim events in Saudi Arabia. This work adds to the current corpus of expertise on green pilgrimage practices by outlining a roadmap for implementing these practices. The shortage of research on green tourism attempts, including green pilgrimage, highlights the significance of these findings. After the worldwide pandemic due to COVID-19, there has been a notable expansion in global tourism, which could potentially help nations address their economic difficulties. Therefore, a comprehensive analysis that includes the pilgrimage, economy, energy, and emissions can effectively address Saudi Arabia's national development concerns.

2. Literature review

Climate change-induced global environmental degradation is a major concern. Recent scholarly investigations have explored different sources of CO_2 emissions as an avenue for mitigating environmental harm (Grossman & Krueger, 1991). Several researchers have examined the concerning related CO_2 emissions, energy usage, and economic change (Kirikkaleli et al., 2022; Kongkuah et al., 2022; Liu et al., 2023). Previous works have confirmed that tourism performs a substantial role in adding pollution (Katircioglu & Katircioglu, 2024; Liu et al., 2022;

Table 1
Summary of the literature review.

Studies (author and year)	Study area (country/region)	Data range	Econometric methods	Results on the relationship with CO_2 emissions (positive/negative)		
				Tourism	Economic growth	Energy use
Zaman et al. (2016)	East Asia & Pacific, European Union, and high-income OECD and Non-OECD nations	2005–2013	Principal component analysis (PCA)	+		+
Dogan and Aslan (2017)	European Union (EU)	1995–2011	Ordinary Least Squares (OLS), FMOLS, DOLS	–	–	+
Balli et al. (2019)	Mediterranean territories	1995–2014	Common Correlated Effects Mean Group (CCEMG) and Augmented Mean Group (AMG)	+	+	
Jebli et al. (2019)	Central and South America	1995–2010	FMOLS and DOLS	–	+	
Ali et al. (2020)	Pakistan	1981–2017	ARDL	+	+	+
Aziz et al. (2020)	Brazil, Russia, India, China, South Africa (BRICS)	1995–2018	FMOLS and DOLS	–	+	
Katircioglu et al. (2020)	Cyprus	1977–2015	ARDL	+	+	+
Khan et al. (2020)	Belt & Road Initiative (BRI) zones	1990–2016	Generalized Method of Moments (GMM)	+	+	+
Leitão and Lorente (2020)	EU		Panel FMOLS, panel DOLS, and GMM	–	+	
Selvanathan et al. (2021)	South Asia	1990–2014	ARDL	+	+	+
Akadiri et al. (2021)	16 island nations	1995–2016	ARDL	–		
Jayasinghe and Selvanathan (2021)	India	1991–2018	ARDL	+	+	+
Nosheen et al. (2021)	Asia	1995–2017	DOLS	+	+	+
Xiangyu et al. (2021)	United States	2000–2018	Quantile ARDL	–		+
Zhang and Zhang (2021)	China	2000–2017	Vector Error Correction Model (VECM)	+	+	+
Khanal et al. (2022)	Australia	1976–2019	ARDL	+	+	+
Raihan et al. (2022)	Argentina	1990–2019	ARDL, DOLS, FMOLS, and CCR	+	+	
Raihan and Tuspekova (2022)	Singapore	1990–2019	DOLS, FMOLS, and CCR	+	–	+
Adebayo et al. (2023)	Thailand	1995–2018	Quantile-on-Quantile Regression (QQR)	+	+	+
Ghaderi et al. (2023)	MENA	1995–2018	PMG (Panel Mean Group), FMOLS, DOLS, and CCEMG	–	+	+
Navarro-Chávez et al. (2023)	Asia-Pacific Economic Cooperation (APEC) regions	1995–2020	DOLS	+	+	+
Nwaeze et al. (2023)	EU	1995–2018	Panel ARDL	+	+	+
Raihan (2023)	Chile	1990–2020	DOLS	+	+	
Raihan et al. (2023)	Egypt	1990–2019	DOLS, FMOLS, and CCR	+	+	+
Ullah et al. (2023)	BRICS	1995–2018	CS-ARDL	–	+	
Farooq et al. (2024)	Gulf Cooperation Council (GCC)	2000–2019	FMOLS and generalized least square (GLS)	+		+
Gan et al. (2024)	Top 80 tourist countries	2001–2018	generalized nested spatial (GNS), spatial error model (SEM), and OLS	+	+	
Hussain et al. (2024)	United States	1995–2019	ARDL	+		+
Katircioglu and Katircioglu (2024)	Malta	1971–2018	ARDL	+		+
Odhiambo (2024)	29 sub-Saharan African (SSA) countries	1995–2019	OLS, FMOLS	+	+	
Purwono et al. (2024)	77 countries	2008–2019	Quantile regression	–	+	
Raihan (2024)	Kuwait	1995–2019	ARDL	+	+	+
Roussel and Audi (2024)	EU	1990–2019	OLS	–	–	+
Voumik et al. (2024)	Asia	1995–2019	CS-ARDL	–	+	+

Navarro-Chávez et al., 2023). As a result, legislators and experts have steered increased attention to studying the environmental impact of tourism. Pigram (1980) piloted the correlation between tourism and the ecosystem. The findings indicated that tourism can have varying effects on environmental quality, ranging from positive to neutral or negative outcomes. Multiple experiments have shown that tourism generates a promoting consequence on CO_2 emissions, with tourism activities contributing to increased waste (Adebayo et al., 2023; Nwaeze et al., 2023). In contrast, Mehmood et al. (2022) and Ullah et al. (2023) have found evidence suggesting that tourism can upgrade environmental quality by cutting CO_2 emissions. Table 1 provides a synopsis of scholarly papers examining the linkage connecting tourism, GDP, usage of energy, and CO_2 emissions.

Diverse investigations have employed the ARDL, DOLS, FMOLS, CCR, and OLS methodologies using time series dataset to explore the link concerning GDP development, tourism, and CO_2 emissions across numerous nations. For example, Balli et al. (2019) in Mediterranean countries, Katircioglu et al. (2020) in Cyprus, Khan et al. (2020) in BRI countries, Selvanathan et al. (2021) in South Asia, Jayasinghe and Selvanathan (2021) in India, Nosheen et al. (2021) in Asian countries, Khanal et al. (2022) in Australia, Raihan et al. (2022) in Argentina, Raihan and Tuspekova (2022) in Singapore, Adebayo et al. (2023) in Thailand, Navarro-Chávez et al. (2023) in APEC states, Raihan et al. (2023) in Egypt, Farooq et al. (2024) in GCC countries, Gan et al. (2024) in top 80 tourist countries, Hussain et al. (2024) in the United States, Katircioglu and Katircioglu (2024) in Malta, Odhiambo (2024) in SSA countries, and Raihan (2024) in Kuwait identified an upward trend between CO_2 emissions and tourism. However, certain studies suggest that tourism may help decrease CO_2 emissions (Table 1). Balli et al. (2019) used CCEMG and AMG approaches; Khan et al. (2020) utilized the GMM technique; Zhang and Zhang (2021) employed the VECM model; and Adebayo et al. (2023) applied the QQR method to discover a positive liaison linking tourism and CO_2 emissions in Mediterranean countryside, BRI nations, China, and Thailand, respectively.

Koçak et al. (2020) analyzed the influence of travel advances on CO_2 releases throughout the top tourist destinations during 1995–2014. Their outcomes indicate an encouraging association involving tourism influxes and CO_2 emissions, implying that an upsurge in tourism appearances is coupled with an expansion in CO_2 emissions. In contrast, the study demonstrates a negative link involving tourism receipts with CO_2 emissions, advising that higher tourism receipts are associated with lower CO_2 emissions. Balsalobre-Lorente et al. (2020) discovered a link connecting GDP development, tourism, usage of energy, and CO_2 emissions in advanced nations. The results point out that when tourism economies stretch a convinced level of development, global tourism can have a positive implication on the environment. A large amount of research has found a connection between higher economic progress and a decline in CO_2 emissions. This can be attributed to increased expenditure on emission-reducing technologies and conservation efforts. Raihan and Tuspekova (2022), alongside Dogan and Aslan (2017), observed a negative correlation relating economic development and carbon emissions in Singapore and EU nations.

Existing empirical research implies that theoretically, tourism might improve or damage the natural world. The current academic literature does not specify clear signs of the knot involving tourist influxes and ecological damage. As a result, it is difficult to uncover the exact consequence of the Hajj pilgrimage tourism on the environment in Saudi Arabia. Additionally, there is an inadequacy in investigating and analyzing the influence of uncertainty surrounding monetary strategies and manmade actions, specifically religious tourism, on CO_2 emissions. This calls for further investigation. Therefore, it is crucial to gauge the nexus involving Hajj traveling and CO_2 emissions in Saudi Arabia to bridge a gap in standing research. The innovation of this investigation reveals the positive upshot of the Hajj pilgrimage on emissions and provides appropriate policy implications and recommendations toward sustainable tourism, green pilgrimage, emission reduction, and ecological sustainability.

3. Methodology

3.1. Data

The work investigated the link between CO_2 emissions and several independent variables, including the number of foreign Hajj pilgrims, GDP growth, and energy utilization. The study analyzed the interrelationships among variables from 1970 to 2019, spanning 50 years. The statistics of CO_2 emissions were obtained from Our World in Data (OWD, 2023), whilst the data on the number of foreign pilgrims were obtained from the Al-Medina Education Centre (AMEC, 2023). The World Development Indicators (WDI) given the GDP dataset (World Bank, 2023). Statistics on energy utilization was obtained from the Statistical Review of World Energy (SRWE, 2023) database. The data for all variables were collected from the official websites of the data sources, and no missing data were identified for the study period from 1970 to 2019. Table 2 presents the logarithmic symbols of the factors as well as the units and sources of data. Fig. 1 displays the annual outlines of the parameters. There is an upsurge in the sum of Hajj pilgrims and GDP expansion, indicating a consistent upward trend. Saudi Arabia has made significant progress in reducing carbon emissions and becoming a global leader in sustainability, as evidenced by the declining trends in energy use and CO_2 pollution in recent times.

Table 3 showcases overview metrics for factors involving statistical evaluations from normality tests and correlations between variables. The dataset comprises 50 observations per variable, and the mean and median exploration of all parameters reveal normality. Skewness points close to zero point toward the variables' normal distribution and exhibit a negative skew. All series demonstrate platykurtosis, with values below 3. A lower Jarque-Bera likelihood suggests that all factors follow a normal distribution. A probability magnitude greater than 0.1 indicates normality. The correlation analysis exhibited a strong positive correlation (Table 4), indicating that an upsurge in one variable is escorted by a resultant growth in the other variable, and vice versa.

3.2. Theoretical framework, empirical model, and analysis procedure

The literature on econometric studies frequently utilizes CO_2 emissions as a substitution for environmental damage. There is a theoretical correlation involving CO_2 emissions, income levels, and energy utilization owing to the prevalent adoption of fossil fuel energies in economic performance. Since CO_2 releases are connected with mutual GDP progress and energy utilization, Equation (1) was built as per the demand function.

$$C_t = f\,(Y_t;\ E_t) \quad (1)$$

Where C_t, Y_t, and E_t are the CO_2 emissions, GDP development, and energy utilization at time t, respectively.

The Hajj is an annual Islamic pilgrimage to Mecca in Saudi Arabia, considered a significant representation of Islamic faith and global unity.

Table 2
Description of the variable.

Variables	Description	Logarithmic forms	Units	Sources
C	CO_2 emissions	LC	Ton	OWD (2023)
H	Hajj pilgrimage	LH	Number of foreign pilgrims	AMEC (2023)
Y	Economic growth	LY	GDP (constant Saudi Riyal)	World Bank (2023)
E	Energy consumption	LE	Joule	SRWE (2023)

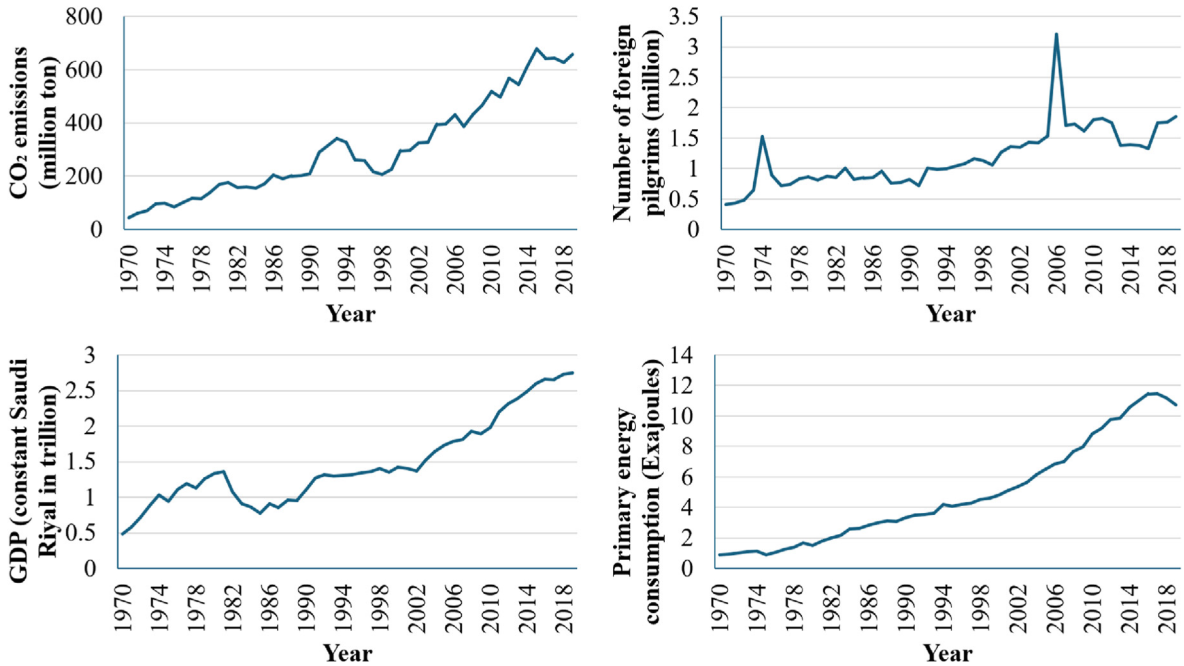

Fig. 1. Annual trends of the variables.

Table 3
Descriptive statistics.

Variables	LC	LY	LE	LH
Mean	19.32	27.94	42.75	13.90
Median	19.38	27.92	42.86	13.86
Maximum	20.34	28.64	43.89	14.98
Minimum	17.63	26.91	41.35	12.91
Std. dev.	0.68	0.41	0.79	0.41
Skewness	−0.42	−0.09	−0.27	−0.14
Kurtosis	2.50	2.69	1.95	2.49
Jarque-Bera	2.00	1.27	2.94	1.26
Probability	0.37	0.50	0.23	0.57

Table 4
Correlation analysis.

	LC	LY	LE	LH
LC	1.00			
LY	0.91	1.00		
LE	0.97	0.87	1.00	
LH	0.83	0.83	0.81	1.00

The Hajj pilgrimage usually lasts for five to six days, occurring from the 8th to the 12th or 13th of Dhul Hijjah. Eid al-Adha begins with the sighting of the new crescent moon and lasts for four days. The pilgrimage entails a series of prescribed rites and rituals that must be followed in a specific sequence. Umrah, also known as the 'minor pilgrimage' or the 'lesser pilgrimage,' is a simplified version of the pilgrimage to the holy city of Makkah. Umrah is a series of rituals that can be performed at any point during the year and can be accomplished within a relatively short duration. Mecca and Medina, being sacred cities, annually draw above three million pilgrims throughout the Dhu al-Hijjah month for Hajj besides approximately two million throughout Ramadan for Umrah. Mecca and Medina host around four million individuals annually to perform Umrah.

The surge in carbon emissions during the Hajj pilgrimage is primarily triggered by the utilization of fossil fuel energy in transportation, accommodation, and related activities. Nations are expanding their financial investment in natural reserves and ecosystems to attract more international tourists. This has both negative possessions on CO_2 emissions initiated by tourism and positive properties on environmental quality (Adebayo et al., 2023; Mehmood et al., 2022; Ullah et al., 2023). This probe identified functional correlations resulting from the Hajj pilgrimage presented below:

$$C_t = f\,(H_t;\ Y_t;\ E_t) \tag{2}$$

where H_t is the amount of Hajj pilgrims at the time t.

Equation (3) exemplifies the empirical model:

$$C_t = \tau_0 + \tau_1 H_t + \tau_2 Y_t + \tau_3 E_t \tag{3}$$

Equation (4) is the econometric framework given below.

$$C_t = \tau_0 + \tau_1 H_t + \tau_2 Y_t + \tau_3 E_t + \varepsilon_t \tag{4}$$

where τ_0 and ε_t are intercept and error term while τ_1, τ_2, and τ_3 are coefficients.

The logarithmic order of Equation (4) can be denoted as follows:

$$LC_t = \tau_0 + \tau_1 LH_t + \tau_2 LY_t + \tau_3 LE_t + \varepsilon_t \tag{5}$$

Where LC_t, LH_t, LY_t, and LE_t are the logarithmic versions of CO_2 emissions, number of Hajj pilgrims, economic progress, and energy usage at time t.

Fig. 2 portrays the diagram illustrating the steps of the assessment procedure. After selecting the information range and constructing the theoretical structure, this study proceeded to assess the stationarity of the data via a unit root test. After confirming the stationarity of the dataset, the analysis is conducted using the ARDL methodology, which involves two steps. After confirming cointegration via the ARDL bounds test, the subsequent step entails conducting long and short-run analyses utilizing the ARDL simulation. This investigation applied the DOLS, FMOLS, and CCR regression structures to authenticate the long-term coefficients attained from the ARDL estimation. Then, it utilized the Pairwise Granger causality test to demonstrate the causal connection linking the factors. In the end, the investigation procedures yielded required suggestions based on the outcomes, limitations, and future research directions.

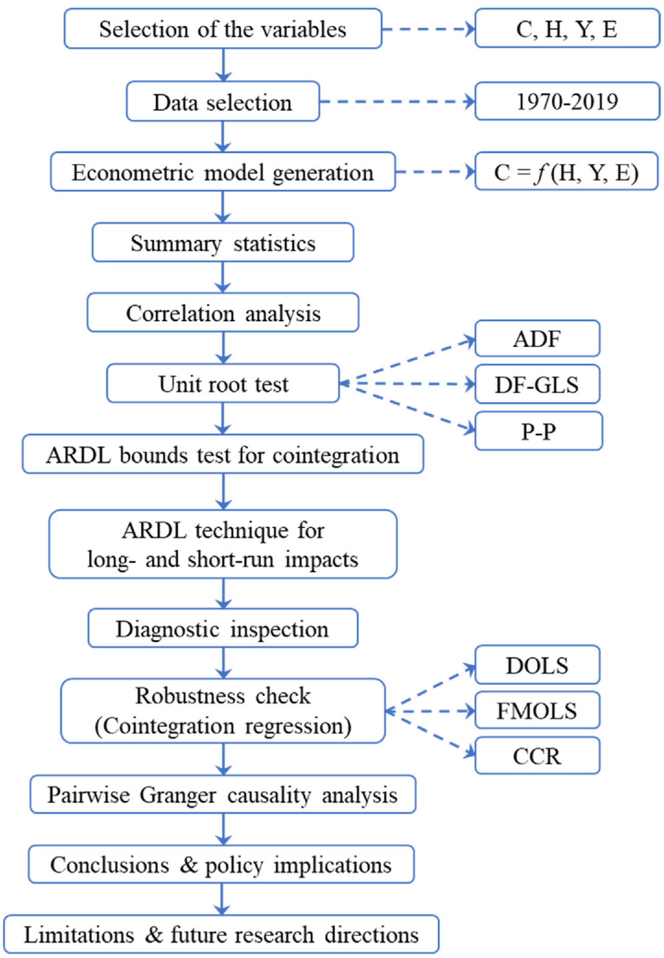

Fig. 2. Flow chart of the analysis.

3.3. Unit root tests

Unit root tests must be done to address false regression. Scholars have acknowledged the importance of deciding the order of integration beforehand investigating the existence of cointegration within factors (Ahakwa et al., 2024; Bertelli et al., 2022; Faisal et al., 2021; Yadav et al., 2022). Multiple unit root tests are crucial for evaluating the integration sequence of a series, as the effectiveness of unit root tests depends on the sample size. This investigation made use of the Augmented Dickey-Fuller (ADF) (Dickey & Fuller, 1979), the Dickey-Fuller generalized least squares (DF-GLS) (Elliott et al., 1996), and the Phillips-Perron (P-P) tests (Phillips & Perron, 1988). This was done to justify the use of the ARDL technique as a substitute for conventional cointegration processes such as OLS, which are unable to calculate the short-run effects of the factors.

3.4. ARDL bounds test

The study employed the ARDL bounds analysis (Pesaran et al., 2001) to discover cointegration between the series. This test is advantageous compared to other single-equation procedures for assessing cointegration (Awan & Yaqoob, 2023; Hussain et al., 2023). The ARDL bounds test is suitable for assessing time series data with mixed series of integration (Shahid et al., 2024). This investigation is obliging because it does not make any compulsory statements and includes all variables for the inquiry in an identical sequence. Additionally, it extends a precise and reliable evaluation of the long-term structure, particularly when working with a petite sample range. The ARDL bounds methodology is applicable regardless of the integration order of the underlying lag system (I(2)), and the cointegration direction can be either I(0) or I(1). The equation for ARDL bounds test and long run simulation is presented below:

$$\Delta LC_t = \tau_0 + \tau_1 LC_{t-1} + \tau_2 LH_{t-1} + \tau_3 LY_{t-1} + \tau_4 LE_{t-1} + \sum_{i=1}^{q} \gamma_1 \Delta LC_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta LH_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta LY_{t-i} + \sum_{i=1}^{q} \gamma_4 \Delta LE_{t-i} + \varepsilon_t \quad (6)$$

where Δ and q are the first differentiation operative and the best lag interval.

In the ARDL limits evaluation, the F-distribution and critical values reported by Pesaran and Timmermann (2005) are applied. The relevance of coefficients of lagged variables is determined using Equation (6) and Ordinary Least Squares (OLS). The experiment seeks to ascertain the probability of a durable statistical association between factors. The null hypothesis (H_0) posits a lack of cointegrating connections. Pesaran et al. (2001) did a comparison involving F-statistics and the precise critical values of upper and lower boundaries. When F-statistics beat the upper critical estimate, indicating a statistically significant long-term affiliation, we reject the null hypothesis. Once the F-statistics plunge beneath the minimal critical projection, the H_0 becomes appropriate. If the F statistics plunge inside the critical thresholds, we cannot draw a definitive conclusion. To handle the ARDL bounds test, this scrutiny determined the lag length by calculating the F-statistic handling of the Akaike Information Criterion (AIC) with the lowest assessments. AIC is an index utilized to assess the relative adequacy of a model, employing information criteria. Akaike (1974) introduced the concept of using the AIC to assess the predictive performance of a model on a given dataset.

3.5. ARDL long- and short-run analysis

This scrutiny incorporated the ARDL simulation to inspect the relationship concerning the factors using together long- and short-range evaluation. The choice of the ARDL approach is justified by previous similar studies (Katircioglu et al., 2020; Jayasinghe & Selvanathan, 2021). After determining the connection of long-term relations, the analysis continues to approximate the error correction term (ECT). The evaluation aims to examine the short-run dynamic range and adjustment rate of the factors headed for their long-run balance. The inclusion of the ECT in the ARDL context, as represented by Equation (7), enables the achievement of this result.

$$\Delta LC_t = \tau_0 + \tau_1 LC_{t-1} + \tau_2 LH_{t-1} + \tau_3 LY_{t-1} + \tau_4 LE_{t-1} + \sum_{i=1}^{q} \gamma_1 \Delta LC_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta LH_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta LY_{t-i} + \sum_{i=1}^{q} \gamma_4 \Delta LE_{t-i} + \theta ECT_{t-1} + \varepsilon_t \quad (7)$$

The velocity of amendment, symbolized as θ, signifies the rate of change. The presence of the lagged error term, ECT_{t-1}, suggests the use of an error correction simulation. The estimated coefficients of ECT typically range from 0 to 1. The ECT enhances the model by establishing that even if the parameters may not be stationary in I(0), their movements are not unsystematic and are connected via a long-term equilibrium correlation.

3.6. Robustness check

Before making any conclusions based on analysis, it is important to gauge the reliability of long-term coefficients acquired commencing the ARDL framework via assessment. This exploration applied the FMOLS, DOLS, and CCR approaches to evaluate the evenness of the ARDL outcomes attained from Equation (6). Some studies in the scholarly literature have demonstrated the suitability of DOLS, FMOLS, and CCR methodologies for validating the ARDL findings (Idroes et al., 2024; Khan & Liu, 2023; Pattak et al., 2023). The existent literature demonstrates the diverse benefits of these methodologies.

The FMOLS (Phillips & Hansen, 1990). procedure uses a semi-parametric approach to project long-run coefficients. This approach effectively addresses concerns related to endogeneity, omitted variable bias, serial correlation, and functional errors, even when applied with a small sample size. Moreover, it considers the occurrence of heterogeneity in long-term characteristics. The FMOLS technique is exploited to approximate a single cointegrating link involving a set of variables that have an integrated order of I(1). This technique primarily transforms data and factors. The FMOLS technique reports the inference challenges present in traditional cointegration methods and provides accurate approximate t-statistics for long-run assessments (Degbedji et al., 2024).

The DOLS (Stock & Watson, 1993) approach employs a parametric method to approximate a long-term link in a model with parameters of varying levels of integration but still exhibiting cointegration. The conclusions of DOLS can be gained from the least squares approximates. These techniques demonstrate the observable qualities of unbiasedness and asymptotic efficiency, even when endogeneity concerns are present. Stock and Watson (1993) suggested that these factors can alter the autocorrelation and non-normality of the residuals.

Additionally, the CCR methodology anticipated by Park (1992) can be used to analyze the existence of cointegrating vectors in a model with an integrated order of I(1). This simulation demonstrates a notable resemblance to FMOLS as to its types. Nonetheless, it is essential to recognize that there is a variation concerning these methodologies. The CCR method mainly focuses on exclusively transforming data, while the FMOLS approach equally emphasizes modifying both data and factors.

3.7. Pairwise Granger causality test

This study applied the pairwise Granger-causality assessment (Granger, 1969) to explore the causal relationship between the features. This study adopts the pairwise Granger causality test to determine the occurrence of unidirectional causality, bidirectional causality, or no causal relationship involving two variables. The cointegration regression conclusions specify coefficients for the independent parameters but do not indicate the occurrence of mutual influence involving any two variables. If a time series Y has predictive power for alternative time series X, it is referred to as "Granger-causing" X. The coefficients can be estimated by means of the OLS assessment, whereas the Granger causality involving X and Y can be identified using F tests. The time series of these two components consists of T data points, denoted as X_t and Y_t ($t = 1, 2, \ldots, T$), representing their respective evaluates at time t. A bivariate autoregressive model can represent the variables X_t and Y_t.

$$X_t = \beta_1 + \sum_{i=1}^{n} \alpha_1 Y_{t-i} + \sum_{i=1}^{n} \mu_i X_{t-1} + e_t \quad (8)$$

$$Y_t = \beta_2 + \sum_{i=1}^{n} \Omega_i Y_{t-1} + \sum_{i=1}^{n} \infty_i X_{t-i} + u_t \quad (9)$$

Where n is the lags number, while β_1, β_2, α_i, Ω_i, μ_i, and ∞_i are considerations for calculation; besides, e_t and u_t are residual terms.

4. Results

Table 5 exhibits the outcomes of the unit root checking conducted during the ADF, DF-GLS, and P-P test investigations. The variables were non-stationary at levels I(0) but converted stationary at the first difference I(1) in all three unit root tests, although the significance levels varied slightly across the tests. The ADF and P-P unit root tests denoted that all factors are stationary at the I(1) with a significance level of 1% ($p < 0.01$). The DF-GLS test showed that LH is stationary at the I(1) with a 1% threshold, while LC, LY, and LE become stationary at the I(1) with a 5% level ($p < 0.05$). These findings reveal that the dataset is appropriate for conducting ARDL analysis.

Table 5
The results of unit root tests.

Variables	ADF		DF-GLS		P-P	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
LC	−2.45	−6.49***	0.51	−2.85**	−2.41	−6.52***
LH	−2.49	−8.80***	−0.77	−8.85***	−2.57	−12.18***
LY	−1.99	−5.36***	0.55	−2.76**	−1.93	−5.30***
LE	−1.28	−7.97***	0.08	−2.98**	−1.38	−7.97***

***$p < 0.01$ and **$p < 0.05$.

Table 6 exhibits the conclusions of the ARDL bounds test, which assesses the circumstance of a cointegration link among the considerations. The upshots confirm a significant long-term relationship flanked by the variables, as shown by the appraised F-statistic (8.58) surpassing the upper bound at 10%, 5%, 2.5%, and 1% levels of significance for both I(0) and I(1), resulting in the refusal of the H_0.

This study researched the implications of the Hajj pilgrimage, GDP extension, and energy usage on CO_2 emissions in Saudi Arabia. The approximate long and short-run results are disclosed in Table 7. The coefficient of LY is negatively significant at a 5% level in both terms. The conclusions suggest that a 1% expansion in economic outgrowth causes a drop of 0.04% and 0.05% in short-term and long-term CO_2 emissions, accordingly. Economic growth can facilitate emissions reduction by directing the augmented GDP towards funding technologies aimed at reducing emissions. The empirical literature suggests a positive correlation relating economic expansion with CO_2 pollution in immediate GDP growth. Once a specific threshold is surpassed, greater GDP growth in an advanced economy is linked to heightened investment in environmental preservation, leading to decreased carbon emissions. The anticipated coefficients of LE demonstrate encouraging and substantial consequences at a 1% level. In Saudi Arabia, a 1% intensification in energy intake is coupled with a short-term increase of 0.91% and a long-term increase of 1.02% in CO_2 emissions. A 1% increase in the quantity of Hajj pilgrims arriving in Saudi Arabia is responsible for a short-term growth of 0.02% in CO_2 outputs and, over time, a surge of 0.03%. The projections rely on the positive coefficients of LH, with a significance level of 5%. The research posits that energy utilization and Hajj pilgrims' arrivals are positively linked with increased CO_2 pollution in Saudi Arabia in both time periods. However, economic growth can facilitate the funding of carbon emission reduction technologies, which can ultimately improve environmental excellence by dropping emissions in the country.

Furthermore, the ARDL simulation's short-term subtleties support the firmness of the long-term coefficients. The ECT coefficient is negatively signed and significant at the 1% level. Annual corrections account for approximately 57% of immediate differences from long-term equilibrium. The long-run evaluation yielded R^2 coefficients of 0.99. The data indicates that the explanatory actors possess the capacity to account for 99% of the observed patchiness in the adjustment of the endogenous parameter. In addition, the RMSE and MAE offer precise evaluations of model forecasts. The RMSE and MAE digits of 0.04 indicate a strong alliance linking the model's forecasts and the factual statistics.

Table 8 indicates the diagnostic assessment calculations for the ARDL simulation. The diagnostic tests undertaken on the ARDL framework imply that it offers high goodness of fit. Although the Breusch-Godfrey Lagrange Multiplier (LM) analysis verifies the dearth of serial

Table 6
Results of ARDL bounds analysis.

Test statistic	Estimate	Significance level	I(0)	I(1)
F-statistic	8.58	10%	2.37	3.20
K	3	5%	2.79	3.67
		2.5%	3.15	4.08
		1%	3.65	4.66

Table 7
ARDL the long- and short-run results.

Variables	Long-run			Short-run		
	Coefficient	t-statistic	p-value	Coefficient	t-statistic	p-value
LY	−0.05**	−2.31	0.03	−0.04**	−2.32	0.03
LE	1.02***	8.52	0.00	0.91***	4.38	0.00
LH	0.03**	2.65	0.03	0.02**	2.61	0.02
C	12.57	2.89	0.02	–	–	–
ECT (−1)	–	–	–	−0.57***	−3.79	0.00
R^2	0.99					
Adjusted R^2	0.99					
RMSE	0.04					
MAE	0.04					

***$p < 0.01$ and **$p < 0.05$.

Table 8
The results of diagnostic tests.

Diagnostic tests	Coefficient	p-value	Conclusion
Functional form	1.34	0.00	No functional error
Jarque-Bera	1.61	0.45	Normal distribution of the residuals
Breusch-Godfrey LM	0.99	0.39	No serial correlation
Breusch-Pagan-Godfrey	1.72	0.18	No heteroscedasticity
Ramsey RESET	1.29	0.22	The model is accurately illustrated

correlation, the Jarque-Bera test suggests that the residuals correspond to a normal distribution. The Breusch-Pagan-Godfrey test establishes the non-appearance of heteroskedasticity, and the Ramsey RESET confirms the model's accurate specification. In addition, the CUSUM and CUSUMSQ tests, shown in Fig. 3, show that the model is stable because the residuals fall contained by the confidence intervals at a 5% significance level.

The robustness of the ARDL approximation was evaluated by incorporating the FMOLS, DOLS, and CCR tests. The conclusions of the models are reliable and consistent, as shown in Table 9. The outcomes observe that higher energy utilization and participation in the Hajj pilgrimage are associated with increased CO_2 emissions. Conversely, long-term CO_2 releases are about to fall with economic growth. It closely aligns with the conclusions drawn from the ARDL results, with only minor variations in statistical significance and coefficient size. In light of the results, it can be determined that the ARDL structures are consistent and validated. The robustness check, employing DOLS, FMOLS, and CCR procedures, yielded accurate statistics. This is evident from the RMSE and MAE values, which were close to zero and non-negative.

Table 10 displays the outcomes of pairwise Granger causality, which includes the causality route concerning the factors, such as unidirectional causality from left to right (→), bidirectional causality (↔), that both factors influence one another, and no causality (≠). The pairwise Granger causality analysis indicates unidirectional causality running from LY to LC, LE to LC, LH to LC, LH to LY, and LH to LE due to statistical significance, heading to the refusal of the H_0. It reveals monetary evolution, energy consumption, and Hajj pilgrimage Granger-cause CO_2 emissions. In addition, the Hajj pilgrimage Granger causes economic growth and energy utilization. Additionally, the test confirms bidirectional causality linking LE and LY, suggesting that energy consumption Granger causes economic expansion and reciprocally. Fig. 4 shows the causal directions connecting the factors. The results of the Granger causality analysis are both theoretically and practically accurate. The Hajj pilgrimage contributes to carbon emissions through the stimulation of economic activities that rely on energy use. Economic expansion is a motive for increased energy use, and in turn, energy utilization contributes to further economic growth. Carbon emissions increase due to this interconnected liaison involving pilgrimage, economy, and energy.

5. Discussion

This probe examined the correlation relating GDP development and ecological ruin in Saudi Arabia. The empirical findings indicate a statistically significant and negative link relating economic extension and carbon emissions. The outcomes suggest a favorable nexus involving GDP and ecological sustainability in Saudi Arabia. This analysis's outcomes align with prior research by Alshehry (2015), Alkhateeb et al. (2020), Kahia et al. (2021), and Ozturk et al. (2022). They constantly demonstrated a negative link between the rise in the economy and CO_2 releases in Saudi Arabia, indicating that higher economic progression will ultimately drop emissions. Moreover, our study's findings are in opposition to Ali et al. (2023), who obtained a positive connection concerning Saudi Arabia's GDP and CO_2 emissions. Nonetheless, it is critical to note that not all types of economic expansion have negative impacts on environmental sustainability. As people's income increases, they are more capable of allocating resources towards environmental conservation and addressing the negative impacts of pollution. Moreover, technological advancements in the economy can lead to enhanced productivity and reduced pollution levels. The growing awareness of environmental concerns, advancements in eco-friendly technology, renewable energy usage, the preference for sustainable lifestyles, and the implementation of sustainable policies are all associated with long-term economic growth (Gong & Chen, 2023).

This inquiry analyzed the consequences of pilgrimage tourism on CO_2 generations. The ARDL test results reveal a positive link between the quantity of Hajj pilgrims arriving in Saudi Arabia and CO_2 emissions. The finding is supported by El Hanandeh (2013), Farahat et al. (2021), and Ozturk et al. (2022). The yearly boost in the number of visitors during Hajj has led to a corresponding rise in human activities and traffic, thereby impacting the air quality of Saudi Arabia (Farahat et al., 2021).

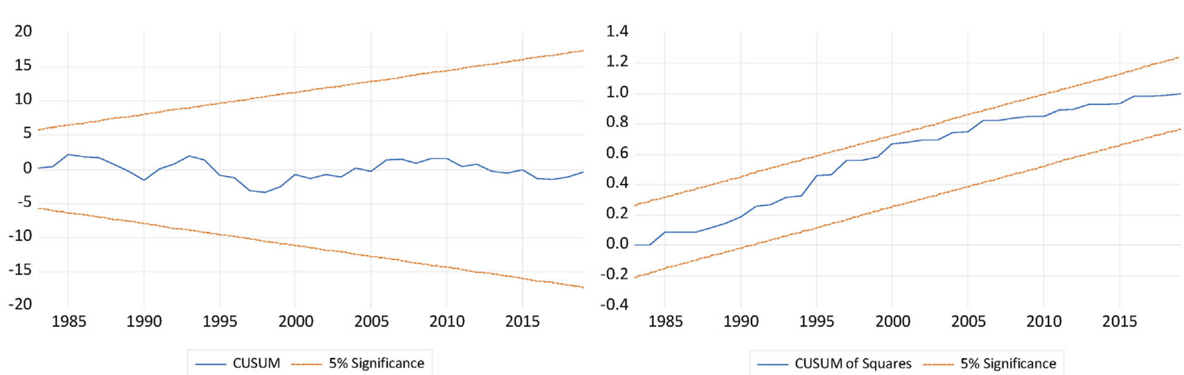

Fig. 3. The CUSUM and CUSUMSQ plots.

Table 9
The results of the robustness check.

Variables	FMOLS		DOLS		CCR	
	Coefficient	t-statistic	Coefficient	t-statistic	Coefficient	t-statistic
LY	−0.08**	−3.11	−0.10**	−2.76	−0.06**	−3.53
LE	1.05***	11.69	1.06***	9.97	1.04***	11.24
LH	0.01**	3.16	0.04**	2.77	0.01**	3.30
C	13.31	4.10	14.18	3.62	12.73	3.70
R^2	0.99		0.99		0.99	
Adjusted R^2	0.99		0.99		0.99	
RMSE	0.04		0.06		0.04	
MAE	0.04		0.04		0.04	

***$p < 0.01$ and **$p < 0.05$.

Table 10
The results of the pairwise Granger causality test.

H_0	F-statistic	Decision on H_0	Causality direction
LY ≠ LC	6.23***	Reject	LY → LC
LC ≠ LY	0.63	Accept	
LE ≠ LC	5.11***	Reject	LE → LC
LC ≠ LE	1.92	Accept	
LH ≠ LC	5.35***	Reject	LH → LC
LC ≠ LH	0.45	Accept	
LE ≠ LY	10.84***	Reject	LE ↔ LY
LY ≠ LE	3.84**	Reject	
LH ≠ LY	6.14***	Reject	LH → LY
LY ≠ LH	0.15	Accept	
LH ≠ LE	5.28***	Reject	LH → LE
LE ≠ LH	0.28	Accept	

***$p < 0.01$ and **$p < 0.05$.

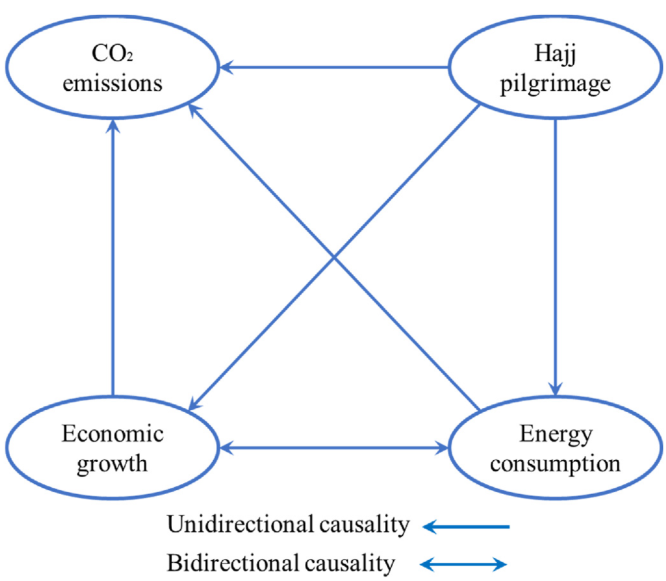

Fig. 4. Granger causality between the variables.

During the Hajj pilgrimage, individuals from various nations worldwide journey by air to King Abdulaziz International Airport, located approximately 85 km away from the city of Mecca. Consequently, pilgrims utilize various modes of local transportation such as buses, cars, and taxis to journey to Mecca. According to Farahat et al. (2021), over 18,000 buses were employed for the transportation of pilgrims to Mecca in 2019. The rise in GHG emissions intensity can be ascribed to air transport, high volumes of road vehicles, and human activities. The Saudi government has addressed the issue of air pollution in Makkah by establishing the CIHUR, which focuses on scientific research. The institute includes an air pollution research unit that focuses on checking and mitigating air toxins in Makkah and Madina.

This research looked at a connection between Saudi Arabia's energy use and pollution levels. This study affirms that fossil fuels serve as the key energy supply in Saudi Arabia, exerting a weighty influence on both short- and long-term CO_2 emissions. The probe uncovered a negative connection relating energy use and environmental conditions in Saudi Arabia. Hence, Saudi Arabia must develop and implement a viable strategy to cut emissions in the energy segment. The Granger causality testing decisions hint that there is a one-way causal link concerning economic advance, energy intake, and pilgrimage tourism to CO_2 emissions in Saudi Arabia. Similar outcomes were reported by Ali et al. (2020) for Pakistan, Udemba (2019) for China, Jayasinghe and Selvanathan (2021) for India, Nosheen et al. (2021) for the Asian region, Gao et al. (2021) for the Mediterranean region, and Ozpolat et al. (2021, pp. 155–175) for top ten tourism-induced countries.

Pilgrimage tourism is crucial for Saudi Arabia's economic development and requires sufficient support and tactical expansion. Hence, it is crucial to spotlight ecological conservation and improvement to achieve sustainable economic development and promote green pilgrimage in Saudi Arabia. Green pilgrimage refers to the integration of the principles of sustainability with the practice of pilgrimage (Elgammal & Alhothali, 2021). The devotion of a green pilgrimage is to enhance destination capacities, promote sustainable and beneficial consequences for the ecosystem and society, and serve as a exemplary for conserving natural resources and reducing emissions. During peak periods of pilgrimage rituals, there is observable evidence of plastic bottles and other forms of trash accumulating along pilgrimage roads. This phenomenon contributes to heightened pollution levels and exacerbates the negative environmental impacts associated with pilgrimage activities. Crowding throughout the pilgrimage is exerting pressure on the natural resources of the sacred sites (Elgammal & Alhothali, 2021). Prior research has investigated air contamination levels in Makkah throughout the periods of Ramadan and Hajj and found that the observed air pollution exceeds both national and international air quality standards. Hence, all stakeholders must prioritize air pollution and road traffic flow to safeguard human health (Farahat et al., 2021).

The seven key areas suggested by the ARC (2014) to make sacred locations greener during the pilgrimage are shown in Fig. 5. As part of this effort, we must uphold and spread the long-standing religious beliefs regarding the natural world. However, if not handled with care and consideration for the environment, religious ceremonies can lead to chaos. Also, people's food choices account for as much as 30 percent of their carbon footprint, so it's important to choose environmentally friendly options like fresh produce grown nearby. This not only helps the local economy but also lessens our bad influence on the environment. It is also important to use water-efficient appliances and to limit water use in sacred areas. In addition, the locations that pilgrims visit should utilize solar and other sustainable energies for everything, including transportation. In addition to banning free plastic bags, composting and reducing, reusing, and recycling might save tons of carbon dioxide. Last but not least, green infrastructure and sustainable practices should be used in religious structures. It is important to inform stakeholders and

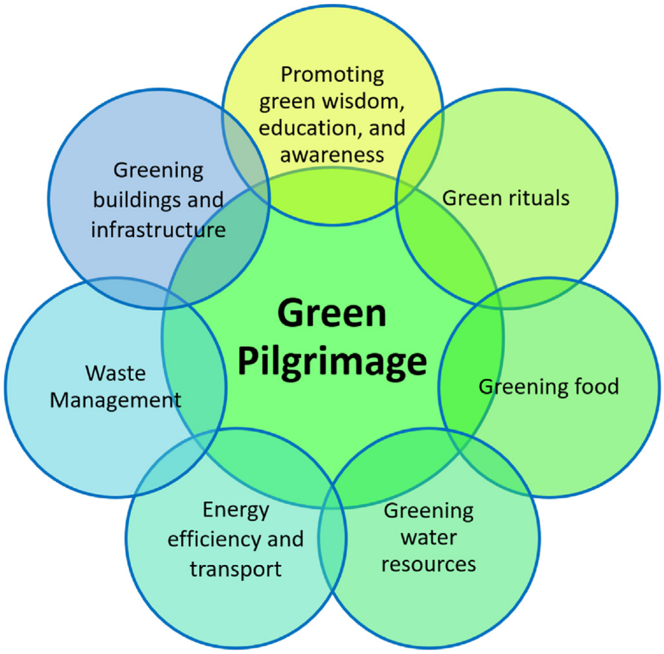

Fig. 5. Key areas of green pilgrimage (ARC, 2014).

visitors of the reasons behind a building's eco-friendliness.

Achieving net zero carbon emissions will bolster Saudi Arabia's international reputation as a sensible global player dedicated to combating climate change. Saudi Arabia has implemented various measures to reduce emissions and transition towards a future with net zero carbon emissions. Saudi Arabia is making sizable investments in renewable energy supplies, comprising solar, wind, and geothermal, alongside energy efficiency technologies. Furthermore, the government has established a goal of making 9.5 GW of renewable power by 2023 and achieving a 50% share of renewable electricity generation by 2030 (EIA, 2023). In addition, the government is implementing measures to encourage energy efficiency, including the Energy Efficiency Law that mandates a 20% reduction in energy consumption for energy-intensive industries. Saudi Arabia is actively working towards enhancing energy efficiency and decreasing energy demand through the utilization of energy-efficient appliances and building materials. This will not only mitigate carbon emissions but also enhance the nation's energy efficiency, resulting in long-term cost savings. Per capita, primary energy consumption has decreased as a consequence of the induction of price reforms and energy efficiency initiatives. The government's subsidies and incentives have led to a rapid surge in the approval of electric vehicles in Saudi Arabia. The country is expected to have more than 1 million electric cars on its roads by 2030, leading to a significant decrease in the nation's reliance on fossil fuels. Green building regulations are being universally adopted in various sectors to enhance energy efficiency and mitigate emissions throughout the entire lifecycle of buildings, encompassing both construction and operation phases. The government is implementing sustainable urban planning strategies, including the development of walkable cities, public transportation options, and green spaces. These initiatives aim to mitigate air pollution resulting from traffic congestion caused by inefficient urban planning practices. Saudi Arabia's actions demonstrate its dedication to transitioning towards a sustainable and carbon-neutral future by embracing renewable energies.

The Saudi Green Initiative is a comprehensive plan aimed at reducing and offsetting carbon emissions to achieve carbon neutrality. Saudi Arabia has pledged to invest in green technology, develop sustainable energy resources, and enhance the deployment of clean energy as part of the initiative. Additionally, it has pledged to enhance environmental conservation efforts and minimize waste generation. The Ministry of Saudi Arabia has implemented a new waste management system at a national level. This system aims to decrease waste generation and encourage recycling practices in all cities of the country. The Deputy Ministry for Environment formulates policies, legislation, rules, strategies, and regulatory frameworks related to adhering to environmental conventions on climate change adaptation. The Deputy-Ministry for Water oversees the mechanisms of conventional and non-conventional water sources, prioritizing their preservation and sustainability as a significant national asset. The Deputy Ministry for Agriculture aims to improve the skills of agricultural industry workers and encourage the use of modern technologies to increase productivity, reduce costs, and implement climate change adaptation strategies.

Additionally, the Kingdom has set up a carbon capture and storage facility to capture and store CO_2 from power plants besides manufacturing activities. As a result, Saudi Arabia was the third fastest reducer of emission growth among the G20 countries. It has adopted the approach of developing a Circular Carbon Economy (CCE) as a way to advance technological innovation toward sustainable and clean energy systems and carbon neutrality. The Kingdom's carbon emissions from fossil fuel consumption had already declined in 2019 and are projected to fall further. Saudi Arabia aims to decrease carbon emissions by 278 million tons annually by 2030 and plans to allocate a budget of up to one trillion riyals ($266.40 billion) towards the development of cleaner energy sources. The country is also developing a national carbon pricing system, incentivizing businesses to invest in clean energy projects. These initiatives are just the beginning of the effort to move Saudi Arabia beyond net zero carbon emissions and make the country a forerunner in the global switch to carbon neutrality.

6. Conclusions and policy implications

6.1. Conclusions

Saudi Arabia is the dominant economy in the MENA area and is responsible for CO_2 emissions due to increased energy consumption related to various economic activities. Saudi Arabia's tourism has witnessed extensive expansion owing to the influx of Hajj pilgrims, resulting in an associated expansion in energy use. This probe empirically scrutinized the liaison concerning the arrival of Hajj pilgrims, energy adoption, GDP rise, and CO_2 releases in Saudi Arabia. The probe utilized data from 1970 to 2019. The stationarity of the dataset was confirmed with ADF, DF-GLS, and P-P unit root assessments. Additionally, the ARDL bounds examination yielded empirical confirmation for the presence of cointegration amidst the considerations. The inferences from the ARDL scrutiny illustrated that a 1% surge in the number of Hajj pilgrims and energy intake advances to a corresponding boost in CO_2 emissions. Specifically, in the short run, encouragement in CO_2 emissions by 0.02% and 0.91% for each respective factor, while in the long run, the increases are 0.03% and 1.02%, respectively. The outcomes specify that a 1% upswing in economic expansion is associated with a drop of 0.04% in CO_2 emissions in the immediate time and 0.05% in the long term. The investigation demonstrates that the environmental consequences of higher numbers of Hajj pilgrims and increased energy consumption are more pronounced in the near and distant future. Increased monetary expansion has long-term effects that are more environmentally sustainable compared to its short-term effects. The estimated results exhibit robustness when using DOLS, FMOLS, and CCR simulations. The pairwise Granger causality test was employed to ascertain the causal connection connecting the parameters. The inquiry supports to the available papers by posing a detailed understanding of the linkage involving pilgrimage, economy, energy, and emissions. Additionally, it highlights the significance of advocating for renewable energy and implementing eco-friendly pilgrimage practices as strategies to reduce emissions in Saudi Arabia. The study's findings provide a reference point for evaluating other religious gatherings or mass events.

6.2. Policy implications

This article proposes policy recommendations for Saudi Arabia to achieve carbon neutrality and promote green pilgrimage. The recommendations focus on encouraging the application of renewable energies, advancing sustainable tourism, and developing a low-carbon economy. Saudi Arabia's GDP heavily depends on the production of oil and gas. Transitioning away from this dependence will require significant investment and innovation, which may pose economic challenges for the country in the near term. Despite the challenges it encounters, Saudi Arabia can assume a prominent position in advancing sustainability. To succeed in net zero carbon emissions, it is necessary to diversify the economy, generate new employment prospects, and enhance economic growth. The study suggests that Saudi Arabian policymakers should make an environmentally friendly policy that efficiently reduces CO_2 emissions whilst also protecting the economic progression fueled by religious tourism. The GCOM in Saudi Arabia supports net zero emissions by allowing companies and entities to compensate for their GHG emissions. GHG emissions can be reduced or eliminated by purchasing credits or certificates from project proponents who voluntarily undertake such actions. The leading objective of the Mechanism is to advance the adoption of credits and certificates of superior quality. These initiatives aim to mitigate pollution from fossil fuel treatment in the energy and tourism segments.

The promotion of renewable energies is essential for mitigating the environmental impacts linked to economic expansion and the extension of the tourism business. Policymakers can assist in the expansion and advancement of alternative power enterprises and technologies. These applications would promote the switch from fossil fuels to renewable energies, thereby contributing to the country's goal of mounting the ratio of green energy to total energy utilization. Achieving net zero carbon emissions requires strong political commitment and dedication from government officials at all levels of governance. Compliance with ecological laws is crucial. These actions aim to balance the Kingdom's objective of achieving swift economic progress and revolution with the preservation of environmental quality.

Saudi Arabia has the potential to assume a protuberant role in sustainability by allocating resources towards renewable energy, enhancing public consciousness, fostering partnerships with the private sector, and actively engaging with international stakeholders. Saudi Arabia is contemplating expanding its ventures in infrastructures and technologies to bolster the implementation of renewable energy. Saudi Arabia aims to enhance its research and development endeavors to explore innovative technologies that can support its transition towards sustainability. Investing in renewable energies can enhance Saudi Arabia's energy security by decreasing dependence on fossil fuels. Technological advancements are the main drivers of enhancements in energy efficiency. Saudi Arabia has the ability to promote innovation in the operation, conversion, and exploitation of energy. Saudi Arabia should enhance its technological support network with technologically superior nations to actively foster the development of its renewable resources. Saudi Arabia should prioritize efforts to boost public awareness regarding energy conservation and efficiency. Governments can employ fiscal tools, such as tax inducements, and financial aid with acquisitions by the authority to foster the adoption of environmentally sustainable energy sources among individuals. The government can utilize media channels to promote its green lifestyle perception and persuade the adoption of low-carbon behaviors and consumption patterns.

The expansion in carbon emissions affected by pilgrimage movements in Saudi Arabia calls for the adoption of strategies to address the environmental consequences of pilgrimage tourism. Pilgrimage tourism initially boosts economic growth but its long-term impact diminishes due to pollution. Hence, policymakers must implement environmental policies to maximize the economic advantages of pilgrimage tourism. To comprehend environmental trends among pilgrims, it is crucial to first identify their behaviors and subsequently enforce appropriate restrictions. An alternative approach could involve implementing a quota system for the pilgrim population. Additionally, it is advisable to boost sustainable energy applications in different pilgrimage events. To lower the ecological consequences of pilgrimage tourism, it is crucial to prioritize the provision of environmentally friendly services, including eco-friendly accommodation and transportation options for pilgrims. It is decisive to align the Hajj pilgrimage sector and its supply chain with policies that aim to achieve the Sustainable Development Goals (SDGs). This includes promoting responsible consumption and adopting environmentally friendly practices.

In Saudi Arabia, an effective strategic approach to address climate change is to prioritize sustainable and low-carbon tourism development, particularly by promoting green pilgrimage. Green pilgrimage practices have the potential to mitigate environmental degradation in Saudi Arabia. This study proposes a framework for green pilgrimage action, which can facilitate the identification and utilization of potential opportunities for its implementation. This study suggests implementing pre-Hajj measures before the pilgrimage event. The process of green pilgrimage entails several steps: identifying motivations for involvement, engaging relevant stakeholders to express their vision and establish agreements, conducting environmental assessments to evaluate positive actions, formulating a strategic plan with specific objectives, and actively participating in the green pilgrimage network while exchanging successful approaches. It is recommended that staff and volunteers undergo training on environmental matters and are encouraged to adopt eco-friendly modes of transportation. Stakeholders should actively monitor the progress of predetermined objectives and implement zero waste stations throughout a pilgrimage. Conducting post-event evaluation and performance measurement for green pilgrimage is crucial and should involve all relevant stakeholders. One strategy to accomplish this objective involves increasing pilgrims' awareness of environmental issues and involving them in the effort by encouraging compliance with guidelines and the adoption of sustainable behaviors.

This study aims to raise perceptions concerning pollution lessening, efficient garbage management practices, and financial support for the preservation of Saudi Arabia's religious and cultural heritage sites. These exertions aim to support transnational tourism growth while also achieving sustainable economic progress, promoting green purchases and manufacturing ways, creating mitigation methods, and ensuring the sustainable usage of natural materials. The objectives are in line with SDGs 7, 8, 12, 13, and 14. This study's conclusions have real-life implications for evaluating ecological policies and establishing an action plan to prepare Saudi Arabia for a world with a temperature increase of 1.5 °C. This analysis proposes investigating the link relating tourism, energy, economy, and environment in emerging regions. The goal is to acquire stability concerning economic growth through tourism and the safeguard of the earth. This study's findings may specify guidelines to additional improving territories seeking to develop successful strategies for achieving sustainable tourism, tho also improving policies for climate change mitigation plus adaptation.

6.3. Limitations and future research directions

A key lack of the research is the deficiency of data ahead of the analysis time, which borders the effectiveness of the econometric methodologies handled. This experiment investigated the relationship between the arrivals of Hajj pilgrims and the generations of CO_2 in Saudi Arabia. Additionally, conducting comparative analyses of pilgrims based on their country of origin could yield valuable insights in future research. Further investigation could be carried out using sophisticated econometric methods to evaluate the association between religious tourism, economy, energy, and emissions. Given the insufficient research available in the current literature, this study proposes prioritizing future research on sustainable tourism, religious tourism, and green pilgrimage in order to achieve environmental sustainability and carbon neutrality. Moreover, future research must take into account other factors that may affect emission growth but were not investigated in the current investigation. These aspects encompass trade liberalization, foreign direct investments, inclusion in finances, urbanization, globalization, and technical advancement, among various others. Furthermore, future studies on the tourism-energy-economy-environment model might include additional relevant aspects such as industry structure, government policies, and technology breakthroughs. This could be achieved by employing more advanced econometric approaches. Besides, further research could involve utilizing consumption-based carbon emissions as a measure of pollution or exploring alternate gauges such as particulate matter (PM 2.5).

CRediT authorship contribution statement

Asif Raihan: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Syed Masiur Rahman:** Writing – review & editing, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Tapan Sarker:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Investigation, Conceptualization.

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.

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