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Bilateral trade of Saudi Arabia in low carbon technology with GCC countries: assessing the impact of economy size and carbon emissions using modified gravity model

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Abstract

Purpose – In 2023, Saudi Arabia led Gulf Cooperation Council (GCC) trade in low-carbon technology (TLCT), exporting over $1.2 billion in solar panels and technologies. Its focus on TLCT trade drives regional sustainability and economic growth, solidifying its role as the GCC's hub for sustainable trade.

Design/methodology/approach – The current study uses a modified gravity model to assess the bilateral TLCT between Saudi Arabia and its trading partners of the GCC. The model uses economic size (mass) as the numerator and carbon emissions ratio as the denominator, replacing the traditional distance variable to account for environmental disparities as trade barriers. Cross-section non-linear autoregressive distributed lag model estimates are used to estimate the modified gravity model.

Findings – The estimates reveal that Saudi Arabia's economic size positively impacts TLCT in both the short and long run, while negative shocks reduce the trade. Similarly, the increase in economic size of trading partners enhances TLCT volumes and vice versa. The higher carbon emissions ratio indicates more emissions in Saudi Arabia relative to its partners, hindering the LCT trade, while a lower ratio facilitates trade by reducing environmental trade barriers.

Originality/value – The current study presents novel and distinct contributions to the literature on trade and sustainability. First, it estimates the dynamics of TLCT that have been underexplored in empirical modelling. Second, it modifies the traditional gravity model of trade by introducing the emissions gap as a trade barrier, thereby integrating environmental performance with TLCT. Third, it applies a non-linear modelling approach to capture asymmetric oscillations in the effects of economic size and the emissions gap on TLCT.

Highlights

(1) The study introduces a modified gravity model, replacing the traditional distance variable with the carbon emissions ratio to assess trade barriers in bilateral low-carbon technology (LCT) trade.
(2) An asymmetric effect of economic size demonstrates that positive changes in Saudi Arabia's GDP and its trading partners' economic size significantly enhance LCT trade, while negative changes reduce it in both the short and long run.
(3) Emissions ratio act is a trade barrier; the negative impact of higher carbon emissions ratios on LCT trade shows that reducing emissions can lower trade barriers and promote sustainable technology diffusion.
(4) The study recommends economic growth policies, emissions reduction strategies and stronger regional collaboration to foster LCT trade and advance environmental sustainability goals.

Keywords Low carbon technology, Trade, Gravity model, CS-NARDL, Saudi Arabia
Paper type Research article

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1. Introduction

Historically, trade has been an engine of economic growth, enabling countries to expand and improve their standard of living through globalization. Nevertheless, its effects on the ecosystem are critical (Dixit, 2014; Mehta, Patel, Joshi, & Patel, 2024). The increased trade volumes have contributed to the development of industries, also rising energy expenditure and increased carbon dioxide (CO_2) emissions, making trade one of the significant contributors to climate change and environmental degradation (Karedla, Mishra, & Patel, 2021). Developing countries, particularly those heavily reliant on trade to drive economic growth, are expected to experience higher energy demand and increased emissions due to their reliance on fossil fuels for industrial and urban development (Adebayo, Saeed Meo, & Özkan, 2024). This trend is consistent with the Environmental Kuznets Curve (EKC) hypothesis, which predicts that CO_2 emissions will rise with economic progress but decrease once countries adopt cleaner technologies and prioritize sustainability (Krishnendu & Patra, 2025). In light of trade expansion, there is a need to control impending dangers and damage, which includes sustainable trade and the greater use of green technologies in the fight against climate change (Bekun, Gyamfi, Köksal, & Taha, 2024). Green trade among countries facilitates technology transfer and innovation spillover, helping countries achieve their sustainable goals. In such cases, trade in low-carbon technologies becomes an essential mechanism for bridging the gap between carbon-intensive economies and their sustainable counterparts (Álamo, 2024; Razelan, Hamidi, Zainuddin, Khairuddin, & Zulkifli, 2024). For countries with high emissions, importing low-carbon technologies (LCT) can enhance energy efficiency, adopt cleaner production methods and fulfil international climate commitments (Razelan *et al.*, 2024). These technologies will be instrumental in reducing dependence on fossil fuels, improving production processes and mitigating the ecological footprint of economic activities (Bai, Han, Rizvi, & Naqvi, 2023). Low-carbon technology trade (TLCT) serves both economic and environmental sustainability, enabling carbon-intensive economies to accelerate their transition to sustainability without entirely relying on domestic innovation (Lee, Olasehinde-Williams, & Gyamfi, 2023).

Saudi Arabia's strategic economic influence positions it as a key driver of regional TLCT, complementing its broader Vision 2030 objective of reducing oil dependency. Through substantial investments in renewable energy, the country has emerged as one of the largest LCT traders in the GCC (IMF, 2023; IRENA, 2023). Bilateral trade flows are positively associated with partner economic size and carbon emissions, as evidenced by Saudi solar exports exceeding $1.2bn in 2023. These developments highlight Saudi Arabia's leadership in advancing regional sustainability and fostering a transition toward green economies (Abro *et al.*, 2022; Ayouni & Zouiri, 2024) (see Figure 1).

The traditional gravity model of trade proposes that bilateral trade is driven by the economic sizes of trading nations and hindered by physical distance (Azu, Adekalu, Isa, & Chiadikobi, 2024; Sanso, Cuairan, & Sanz, 1993). However, in the context of low-carbon technologies, geographic distance alone fails to capture the complexities of trade barriers, as environmental differences, such as carbon emissions among trading nations, also act as barriers (Maalel, 2024; Sadiq *et al.*, 2024). In nations with high emissions, mounting pressure is being exerted on them, compelling them to address environmental problems. Countries seeking to reduce carbon emissions can either foster domestic innovation in green technologies or trade to acquire low-carbon technologies (LCT) from environmentally advanced nations (Mehta, 2024). With advances in modern transport and digital integration, geographic distance is no longer the dominant trade barrier. Instead, in the case of LCT, the emissions gap between trading partners becomes the crucial determinant of trade flows. This study introduces a novel gravity model that replaces distance with the emissions ratio, highlighting how environmental compatibility drives LCT exchanges. A higher emissions ratio reflects greater urgency for green adoption, often stimulating technology transfer toward high-emission countries. Such disparities, while challenging, also create opportunities for cooperation, advancing sustainability goals. For Saudi Arabia, this framework aligns with

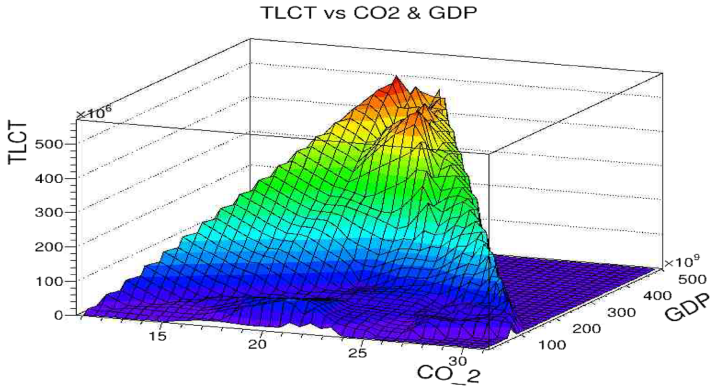

Figure 1. Bilateral trade in LCT, carbon emissions and economic size of GGC countries. Source: Author's calculation using Python, based on the data retrieved from https://climatedata.imf.org/pages/go-indicators#gp1 and https://databank.worldbank.org/source/world-development-indicators; TLCT indicates bilateral trade in low carbon technology of GCC countries, CO_2 indicated carbon emissions of GCC countries and GDP indicated economic size of the GCC countries

Vision 2030, supporting diversification beyond oil and reduced carbon intensity. Strengthening GCC-level technology partnerships through joint research, investment and innovation hubs will accelerate LCT adoption, fostering economic resilience and sustainable regional growth.

The current study presents three novel and distinct contributions to the literature on trade and sustainability. First, it estimates the direction of LCT trade, a niche yet important approach that has been underexplored in empirical modelling, particularly in light of the rising need for achieving the net-zero target. Second, it modifies the traditional gravity model of trade by introducing the emissions gap as a trade barrier, thereby directly integrating environmental performance disparities into the modern trade framework. Third, it applies a non-linear modelling approach to capture asymmetric oscillations in the effects of economic size and the emissions gap on TLCT, providing a more realistic understanding of how these factors influence trade dynamics under varying conditions. The study also highlights how environmental disparities can be addressed by technology diffusion, thereby offering a new dimension for cross-border sustainability linkages.

2. Literature review

The traditional gravity model of bilateral trade is derived from physics, serving as a fundamental construct for trade analysis. According to the gravity model of trade, bilateral trade between two countries is directly dependent on their economic sizes (measured by GDP) and inversely related to the geographical distance between trading partners (Anderson, 1979). The traditional gravity model has been refined over the decades to include additional explanatory variables, such as shared borders, common languages, colonial histories and trade agreements, thereby enhancing the model's capacity to explain trade dynamics (Baier & Bergstrand, 2007; Baltagi, Egger, & Erhardt, 2024), found that the gravity model explains the interdependency of economic impacts on bilateral trade flow, especially in growing globalization. Both researchers and policymakers can significantly benefit from the gravity model's ease of use and empirical accuracy (Ravi Kumar, Reddy, Shafiwu, & Mohan Reddy, 2024). Gravity models can now be applied in modern contexts, such as digital trade and climate change mitigation measures, due to these methodological advancements (Jadhav & Ghosh, 2024).

By using distance as a proxy for trade barriers, the conventional trade gravity model is criticized for oversimplifying trade barriers (Luckstead, Devadoss, & Zhao, 2024). Distance is no longer a hindrance for trade in developed nations with modern transportation, especially for landlocked nations (Dettmer, 2014). In the case of LCT trade, the direction of TLCT is not determined by distance but rather by the emissions difference between trading partners (Wang, Zhang, & Li, 2024). Environmental compatibility between trading partners is analogously linked to the emissions gap (Wang & Zhang, 2021). A larger emissions ratio suggests that the nation with the highest emissions has to embrace greener technologies more, which frequently drives trade flows in low-carbon technologies. Moreover, the limitations include the endogeneity issue, biases associated with missing variables and the assumption of linear trade flows (Capoani, 2024; Sertić, Vučković, & Andabaka, 2024). Furthermore, when it comes to trade that is affected by shocks or external disturbances, traditional approaches are inadequate in capturing dynamic and asymmetric interactions (Luckstead *et al.*, 2024). When examining trade that is impacted by variables like carbon emissions, technology transfer, or geopolitical events, the cross-sectional nonlinear autoregressive distributed lag (CS-NARDL) model fills these gaps by enabling the modelling of both long-run and short-run asymmetries (Ongan & Gocer, 2025). Further studies, such as those by Triki, Kahouli, Tissaoui, and Tlili (2023) conducted in the context of Saudi Arabia, have utilized the NARDL model and found a strong and positive relationship between renewable energy transition, facilitated by technological advances and significant improvement in its economic footprint (AlNemer, Hkiri, & Tissaoui, 2023). They have also utilized the NARDL model and found that Saudi Arabia, being a fossil fuel-based economy, and its reliance on non-renewable energy lead to environmental degradation. As it transitions to more renewable energy, this will result in a more sustainable energy mix. Similarly, the CS-NARDL model is used by Tissaoui and Zaghdoudi (2025) to capture the non-linear effect of variables on environmental degradation for a panel of OECD countries. Thus, using the CS-NARDL model enhances the explanatory power of gravity models by incorporating both positive and negative shocks in the explanatory variables, making them more suitable for contemporary trade assessments (Mehta & Derbeneva, 2024).

The conventional trade gravity model is dynamic and relevant if it can incorporate the changing economic realities, such as including the impact of free trade agreements and non-tariff barriers (Warin & Stojkov, 2024). Furthermore, studies highlight the model’s role in evaluating the trade effects of geopolitical tensions and regional trade agreements (Cevik, 2023; Hakobyan, 2023). Despite its prominence, the gravity model has limitations, such as its reliance on distance as a proxy for trade costs, which may overlook other barriers such as cultural differences and regulatory constraints (Mostafiz, Akter, & Rahman, 2024). The gravity model’s ability to integrate new variables ensures its continued relevance in addressing modern trade challenges (Warin & Stojkov, 2024). The studies like Adams, Attah-Boakye, Yu, Chu, and Mali (2024) and Duarte, Pinilla, and Serrano (2018) highlight that the model may be used for other than traditional commodities in a range of sectors, such as digital services and low-carbon technologies. Recent applications, such as those by Abhishree (2024), have underscored the model’s utility in understanding trade in low-carbon technologies and its potential to promote sustainable development.

The review of literature highlights several evident research gaps such as the previous studies have utilized linear models to estimate bilateral trade; however, non-linear models could yield more dynamic results (Ongan & Gocer, 2025). Furthermore, while the gravity model has been widely used to analyze bilateral trade patterns and the factors influencing trade flows, there is a noticeable gap in its application to trade in low-carbon technology (TLCT). This area is particularly important as the global community faces increasing pressure to address climate change and transition to sustainable economic practices. Trade in low-carbon technologies facilitates the spread of innovations that reduce greenhouse gas emissions, enhance energy efficiency and promote the use of renewable energy (Abhishree, 2024; Zhong, Goh, & Su, 2022). Despite its significance, relatively few studies have explored the dynamics of TLCT using the gravity framework, leaving a crucial aspect of environmental sustainability under-researched. Examining trade in low-carbon technologies through the gravity model and modifying it by taking the emissions gap as a trade barrier can provide valuable insights into how factors such as economic size and carbon emissions can influence the bilateral trade of TLCT. This study addresses a critical gap in the literature by using a modified gravity model for measuring the impact of economic size and carbon emission ratio on TLCT, which is a novel model for estimating the bilateral trade flow of LCT.

3. Methodology

This study quantifies the effect of CO_2 emissions and economic size on Saudi Arabia's bilateral trade in low-carbon technology with selected [1] partners: Oman, United Arab Emirates (UAE), Bahrain and Kuwait. A modified gravity model (MGM) is applied. MGM examines how economic size and carbon emissions impact bilateral trade in low-carbon technology flows between Saudi Arabia and its neighboring countries. The traditional trade gravity model predicts that trade is directly related to economic size and inversely related to physical distance (Sanso *et al.*, 1993; Tiits, Kalvet, Ounoughi, & Ben Yahia, 2024). Here, by taking Oman, UAE, Bahrain and Kuwait, which are landlocked countries with Saudi Arabia, we able to replace physical distance with the ratio of carbon emissions between Saudi Arabia and its trading partner to reflect environmental proximity more accurately.

In this modified model, bilateral trade in low-carbon technology green trade flows $TLCT_{ij}$ are expressed as a function of the economic sizes (measured by GDP) of Saudi Arabia ($country\, i$) and its trading partner $(country\, j)$, along with the ratio of their carbon emissions. Specifically, the emissions ratio is calculated as Saudi Arabia's carbon emissions $(CO2\, Emissions_i)$ divided by the trading partner's emissions $(CO2\, Emissions_j)$. This approach (Eq.1) captures how variations in environmental performance and carbon intensity between the two countries may influence bilateral trade in low carbon technology:

$$TLCT_{ij} = \varnothing \frac{GDP_i X GDP_j}{ER_{ij}} \tag{1}$$

In Eq. (1), the ER_{ij} represents the ratio of Saudi Arabia's carbon emissions $(CO2_i)$ to its trading partner's emissions $(CO2_j)$, while $\varnothing$ is a constant term that scales the equation to ensure appropriate trade flow units (Lohani, 2024). This constant does not vary with other variables but adjusts baseline trade levels to fit the model to the data effectively. Table 1 represents the variables description and source of the annual panel data from 2000 to 2023.

3.1 Model

The CS-NARDL model is used to estimate the modified gravity model of Eq. (1). CS-NARDL model allows to estimate the positive and negative changes in economic size and emissions ratio (see Eqs (2)–(4)).

$$GDP_{it} = GDP_{it}^{+} + GDP_{it}^{-} \tag{2}$$

$$GDP_{jt} = GDP_{jt}^{+} + GDP_{jt}^{-} \tag{3}$$

$$ER_{ij,t} = ER_{ij,t}^{+} + ER_{ij,t}^{-} \tag{4}$$

where GDP_{it}^{+} and GDP_{it}^{-} are positive and negative changes in Saudi Arabia's economy size; GDP_{jt}^{+} and GDP_{jt}^{-} are positive and negative changes in the economy size of Oman, the United Arab Emirates (UAE), Bahrain and Kuwait; $ER_{ij,t}^{+}$ and $ER_{ij,t}^{-}$ are positive and negative changes

Table 1. Data description and sources

Variable	Variable representation	Description and measure	Source
Dependent variable			
Low carbon technology trade	$TLCT_{ij}$	*Description:* This represents the log value of bilateral trade in low carbon technology products from exporter or source countries (for imports) to imports. Trade in Low carbon technologies include mechanics like wind turbines, solar panels, biomass systems and carbon capture equipment	Government Policy Indicators, Climate change Dashboard IMF
Independent variables			
Economy size of Saudi Arabia	GDP_i	*Description:* This represents the log value of total economic output per individual belonging to the Saudi Arabia	World Development Indicators, World Bank
Economy size of neighboring countries	GDP_j	*Description:* This represents the log value of total economic output per individual belonging to the Oman, United Arab Emirates (UAE), Bahrain and Kuwait	
Carbon dioxide emissions of Saudi Arabia	$CO2_i$	*Description:* This shows the per capita emission of the carbon dioxide in metric tons of Saudi Arabia	Government Policy Indicators, Climate change Dashboard IMF
Carbon dioxide emissions of neighboring countries	$CO2_j$	*Description:* This shows the per capita emission of the carbon dioxide in metric tons of the Oman, United Arab Emirates (UAE), Bahrain and Kuwait	
Emission Ration	ER_{ij}	*Description:* This represents the ratio of Saudi Arabia's carbon emissions $(CO2_i)$ to its trading partner's emissions $(CO2_j)$	

Source(s): Compiled by the author and retrieved from https://climatedata.imf.org/pages/go-indicators#gp1and https://databank.worldbank.org/source/world-development-indicators

in ratio of Saudi Arabia's carbon emissions $(CO2_i)$ to its trading partner's emissions $(CO2_j)$. Eqs (5)–(7) represent partial decomposition of Eqs (2)–(4).

$$\begin{cases} GDP_{it}^{+} = \sum_{w=1}^{t} \Delta GDP_{iw}^{+} = \sum_{w=1}^{T} Max(\Delta GDP_{iw}, 0) \\ GDP_{it}^{-} = \sum_{w=1}^{t} \Delta GDP_{iw}^{-} = \sum_{w=1}^{T} Min(\Delta GDP_{iw}, 0) \end{cases} \tag{5}$$

$$\begin{cases} GDP_{jt}^{+} = \sum_{w=1}^{t} \Delta GDP_{jw}^{+} = \sum_{w=1}^{T} Max\left(\Delta GDP_{jw}, 0\right) \\ GDP_{jt}^{-} = \sum_{w=1}^{t} \Delta GDP_{jw}^{-} = \sum_{w=1}^{T} Min\left(\Delta GDP_{jw}, 0\right) \end{cases} \tag{6}$$

$$\begin{cases} ER^{+}_{ij,t} = \sum_{w=1}^{t} \Delta ER^{+}_{ij,w} = \sum_{w=1}^{T} Max\left(\Delta ER_{ij,w}, 0\right) \\ ER^{-}_{ij,t} = \sum_{w=1}^{t} \Delta ER^{-}_{ij,w} = \sum_{w=1}^{T} Min\left(\Delta ER_{ij,w}, 0\right) \end{cases} \tag{7}$$

The short-run CS-NARDL model (Eq. (8)) applies a non-linear framework to the modified gravity model, evaluating how economic size and emissions ratios affect Saudi Arabia's low-carbon trade. To address cross-sectional dependence, cross-sectional averages [2] of dependent and independent variables are included, capturing shared country-level influences.

$$\begin{aligned} \Delta TLCT_{ij,t} = \alpha_{ij} &+ \sum_{p=1}^{P} \beta^{+}_{ij,p} \Delta GDP^{+}_{i,t-p} + \sum_{p=1}^{P} \beta^{-}_{ij,p} \Delta GDP^{-}_{i,t-p} + \sum_{r=1}^{R} \rho^{+}_{ij,r} \Delta GDP^{+}_{ij,t-r} \\ &+ \sum_{r=1}^{R} \rho^{-}_{ij,r} \Delta GDP^{-}_{ij,t-r} + \sum_{q=1}^{Q} \delta^{+}_{ij,q} \Delta ER^{+}_{i,t-q} + \sum_{q=1}^{Q} \delta^{-}_{ij,q} \Delta ER^{-}_{i,t-q} \\ &+ \sum_{s=1}^{S} \tau_s \overline{GDP}_t + \sum_{b=1}^{B} \sigma_b \overline{ER}_t + \sum_{h=1}^{H} \vartheta_h \overline{TLCT}_t + \mu_{ij} \Pi_{t-1} + \varepsilon_{ij,t} \end{aligned} \tag{8}$$

where $\beta^{+}_{ij,p}$ and $\beta^{-}_{ij,p}$ are short-run coefficients for positive and negative changes in GDP_{it}; $\rho^{+}_{ij,r}$ and $\rho^{-}_{ij,r}$ are short-run coefficients for positive and negative changes inGDP_{jt}; $\delta^{+}_{ij,q}$ and $\delta^{-}_{ij,q}$ are short-run coefficients for positive and negative changes in $ER_{ij,t}$; $\tau_s, \sigma_b, \vartheta_h$ are coefficients for cross-sectional averages. Π_{t-1}, is error correction term to measure the rate of adjustment of short-run to long-run equilibrium. The long run CS-NARDL model is presented in Eq. (9),

$$\begin{aligned} TLCT_{ij,t} = \varnothing_{ij} &+ \varphi^{+}_{ij} GDP^{+}_{it-1} + \varphi^{-}_{ij} GDP^{-}_{it-1} + \psi^{+}_{ij} GDP^{+}_{j,t-1} + \psi^{-}_{ij} GDP^{-}_{jt-1} + \lambda^{+}_{ij} ER^{+}_{j,t-1} \\ &+ \lambda^{-}_{ij} ER^{-}_{jt-1} + \epsilon_{ij,t} \end{aligned} \tag{9}$$

where φ^{+}_{ij} andφ^{-}_{ij}; ψ^{+}_{ij} and ψ^{-}_{ij}; λ^{+}_{ij} and λ^{-}_{ij} are long-run coefficients for positive and negative changes inGDP_{it}, GDP_{ijt} and $ER_{ij,t}$, respectively.

4. Results and discussions

The descriptive statistics are presented in Table 2. The Jarque-Bera test statistics indicate that $TLCT_{ij}$, GDP_j and ER_{ij} exhibit relatively symmetric distributions, while GDP_i shows a deviation from normality. Pairwise correlations reveal significant positive relationships between $TLCT_{ij}$ and both GDP_i ($r = 0.5549$) and GDP_j ($r = 0.7522$), suggesting that larger economic sizes drive trade flows. In contrast, ER_{ij} demonstrates a negative correlation with $TLCT_{ij}$ ($r = -0.7580$), indicating an inverse relationship. These results underscore the interconnectedness of economic size, emissions ratio and trade flows within the panel data.

The study utilized a panel unit root test to determine the stationarity of the panel data for the specified variables (see, Im, Pesaran, & Shin, 2003; Levin, Lin, & James Chu, 2002). One of the benefits of using CS-NARDL models is that they can be estimated even when some variables are stationary at the I(0) level while others are at the I(1) level. According to the unit root estimates presented in Table 3, all variables exhibit stationarity at the I(1) level of integration.

Table 2. Descriptive statistics and pairwise correlation

	$TLCT_{ij}$	GDP_i	GDP_j	ER_{ij}
Mean	17.74613	26.98034	25.09305	0.710503
Median	17.63493	27.25427	25.16263	0.704444
Std. dev.	1.205791	0.565056	1.070014	0.176321
Skewness	0.196512	−0.668843	−0.098522	0.123827
Kurtosis	3.065221	2.138422	2.115240	2.181684
Jarque-Bera	0.634887	10.12688	3.286505	2.923897
Probability	0.728008	0.006324	0.193350	0.231784
Observations	96	96	96	96
Pairwise correlation				
$TLCT_{ij}$	–			
GDP_i	0.5549***	–		
GDP_j	0.7522***	0.4799***	–	
ER_{ij}	−0.7580**	0.3866***	−0.1756*	–

Note(s): ***, **, * indicates significant at 1%, 5% and 10% level of significance, respectively
Source(s): Author's calculations from Eviews

Table 3. Second-generation unit root test

Variables	CADF	CIPS
$TLCT_{ij}$	−3.5517***	−3.6856***
$\Delta TLCT_{ij}$	−6.4525***	−7.7412***
GDP_i	−0.6635	−0.6053
ΔGDP_i	−4.5573***	−4.6564***
GDP_j	−1.4674*	−1.3371*
ΔGDP_j	−3.7769***	−3.7091***
ER_{ij}	−1.3641*	−1.2577
ΔER_{ij}	−2.4544***	−2.4651***

Note(s): ***, **, * indicates significant at 1%, 5% and 10% level of significance, respectively
Source(s): Author's calculations from Eviews

Cross-sectional dependence (CSD) is a major issue in panel data analysis because countries often share common shocks or similar structural characteristics that influence their outcomes (Gaibulloev, Sandler, & Sul, 2014). Traditional panel models assume independence across cross-sections, but this is unrealistic in macroeconomic or trade-related studies. As highlighted by (Breusch & Pagan, 1980; Pesaran, 2004), ignoring CSD can bias parameter estimates and mislead inferences. The CSD test rejects independence, showing BRICS interconnections. Incorporating cross-sectional averages in Eq. (8) captures shared dynamics, controls dependence and ensures consistent, robust and policy-relevant estimates across countries.

Table 4 confirms a long-run cointegration among variables. Using CS-NARDL with the pooled mean group (PMG) method, the study estimates the impact of economic size and emissions ratio on low-carbon trade. Supported by the Hausman test, PMG ensures homogeneous long-run equilibrium while capturing short-run heterogeneity, reinforcing robustness (Asteriou, Pilbeam, & Pratiwi, 2021; Hashem Pesaran, Shin, & Smith, 1999).

4.1 Impact of economic size on trade in low carbon technology

The long-run estimates from the CS-NARDL model indicate that both Saudi Arabia's economic size and that of its trading partners significantly and asymmetrically impact TLCT. A 1% increase

Table 4. CSD and panel cointegration tests

Cross-section	$TLCT_{ij}$	GDP_i	GDP_j	ER_{ij}
LM $_{\text{Breusch-Pagan}}$	77.8538***	144.00***	136.80***	56.6226***
LM $_{\text{Pesaran scaled}}$	20.7424***	39.8371***	37.7600***	14.6135***
CD $_{\text{Pesaran}}$	8.6461***	12.000***	11.6944***	5.0798***

Panel cointegration
Panel: pedroni cointegration common AR coefficients (within-dimension)

	Statistic	Weighted statistic
$\boldsymbol{P_v}$	−0.1331**	−0.3786**
$\boldsymbol{P_{rho}}$	−1.6020**	−1.8877**
$\boldsymbol{P_{pp}}$	−5.8003***	−6.6625***
$\boldsymbol{P_{ADF}}$	−4.6630***	−4.8633***

Group: pedroni cointegration individual AR coefficients (between-dimension)

	Statistic
G_{rho}	−0.98344**
G_{pp}	−7.6973***
G_{ADF}	−5.6277***

Note(s): ***, **, * indicates significant at 1%, 5% and 10% level of significance, respectively. P_v, P_{rho}, P_{pp},and P_{ADF} denotes panel statistics and G_{rho}, G_{pp} and G_{ADF} denotes group statistics
Source(s): Author's calculations from Eviews

in GDP_{it}^{+} corresponds to a 1.73% rise in$TLCT_{ij}$. Conversely, a 1% decrease in GDP_{it}^{-} leads to a 1.69% reduction in $TLCT_{ij}$. These results align with the gravity model (Eq.1), which asserts that the economic size of trading partners directly influences bilateral trade flows. A larger economy in Saudi Arabia signals greater production capacity and demand, thereby enhancing the trade of low-carbon technologies. The economic size of Saudi Arabia's trading partners GDP_j also plays a critical role in determining $TLCT_{ij}$. The long-run results show that a 1% increase in $GDP_{j,t}^{+}$ results in a 2% rise in $TLCT_{ij}$, while a 1% decline in ΔGDP_{jt}^{-} leads to a 0.90% decrease in $TLCT_{ij}$. This supports the gravity model's prediction that larger economies of trading partners facilitate higher trade flows due to increased purchasing power and demand for technology.

In the short run, these effects remain asymmetric but are less pronounced. A 1% positive change in Saudi Arabia's ΔGDP_{it}^{+} increases $TLCT_{ij}$ by 0.74%, while a 1% negative change ΔGDP_{it}^{-} decreases $TLCT_{ij}$ by 0.61%. For trading partners, a 1% increase in $\Delta GDP_{j,t}^{+}$ raises $TLCT_{ij}$ by 0.64%. However, a 1% decrease in ΔGDP_{jt}^{-} reduces $TLCT_{ij}$ by 1.97%. These short-term findings demonstrate the immediate responsiveness of $TLCT_{ij}$ to economic fluctuations, in line with the gravity model's core principle that economic size drives trade flows. Overall, the findings highlight the relevance of the gravity model in explaining the trade of low-carbon technologies. The economic sizes of both Saudi Arabia and its trading partners are essential determinants of $TLCT_{ij}$, confirming the multiplicative relationship proposed by the gravity model between the economic sizes of trading countries and their bilateral trade flows.

4.2 Impact of emissions ratio on trade in low carbon technology

The long-term estimates from the CS-NARDL model indicate a significant and asymmetric effect of ER_{ij} on $TLCT_{ij}$. Specifically, a 1% increase in $ER_{j,t}^{+}$ (suggesting that Saudi Arabia's carbon emissions are relatively higher than those of its trading partner) leads to a 6.31%

decrease in $TLCT_{ij}$. This finding suggests that higher carbon intensity in Saudi Arabia compared to its trading partner discourages TLCT, likely due to a misalignment in environmental performance. Conversely, a 1% negative shock in $ER^{-}_{j,t}$ (indicating that Saudi Arabia's carbon emissions are relatively lower than those of its trading partner) results in a 2.34% increase in $TLCT_{ij}$. This indicates that improved environmental performance on Saudi Arabia's part makes it a more attractive partner for LCT exchanges. In the short term, the effects of ER_{ij} remain significant but less pronounced. A 1% positive change in $\Delta ER^{+}_{j,t}$ reduces $TLCT_{ij}$ by 1%, while a 1% negative change in $\Delta ER^{-}_{j,t}$ increases $TLCT_{ij}$ by 0.89%. These short-run dynamics underscore the immediate impact of changes in relative carbon intensity on green trade flows. The results suggest that Saudi Arabia's higher carbon emissions compared to its trading partners suppress its LCT trade potential and vice versa. The significant negative coefficient in the long run underscores the importance of aligning domestic emissions standards with those of trading partners to maintain market access for LCT. Short-run effects, although smaller, indicate immediate trade sensitivity. However, policy tools such as targeted export incentives or temporary tariff adjustments for LCT will hedge against the environmental performance gaps, providing a solution to this issue.

Since ER_{ij} is the denominator in the modified gravity model (see, Eq. (1)), its role is crucial in determining trade flows. A higher ER_{ij} (indicating a greater disparity in carbon emissions) decreases the trade potential for low-carbon technologies, while a lower ER_{ij} (indicating closer alignment in carbon emissions) facilitates such trade. These findings align with the theoretical framework of the gravity model, emphasizing the importance of environmental performance in shaping bilateral trade relationships in green technologies (Abhishree, 2024). The negative and significant error correction term Π_{t-1} indicates an adjustment rate of 1.32% from long-run equilibrium to short-run equilibrium. Table 5 also presents that the cross-sectional averages of $\overline{GDP}_t$, renewable energy $\overline{ER}_t$ and trade liberalization $\overline{TLCT}_t$ are significant. The positive and significant average of $\overline{GDP}_t$ suggests that an increase in economic size increases bilateral trade, indicating a strong relationship between economic size and trade flow. In contrast, the significant negative relationship with the average emission ratio $\overline{ER}_t$ indicates that higher emission ratios are associated with reduced trade flows, suggesting an inverse relationship between environmental degradation and trade volume. Furthermore, the significant results of the asymmetric Wald test in the CS-NARDL model confirm that both positive and negative shocks in the variables have asymmetric effects, highlighting the model's ability to capture dynamic relationships in trade flows over different periods. The model diagnostics estimates presented in Table 5 of LM statistic confirm no autocorrelation, the RESET test shows no significant specification error and the R-squared value of 0.78 demonstrates strong explanatory power. Moreover, the significant ADF statistic of the residuals confirms that the residuals are stationary at I(0), validating the long-run equilibrium relationship captured by the model. The cumulative sum (CUSUM) and cumulative sum of square (CUSUMSQ) graphs also confirm model stability (see Figure 2).

5. Conclusion

This study investigates the relationship between Saudi Arabia's bilateral TLCT and the economic size and carbon emissions ratio of its trading partners—Oman, UAE, Bahrain and Kuwait—using panel data from 2000 to 2023. A modified gravity model replaces the traditional distance variable with the emissions ratio, while the CS-NARDL framework captures both short- and long-run asymmetries. Results show that Saudi Arabia's GDP growth significantly enhances LCT trade, with positive shocks driving higher trade volumes and negative shocks reducing them. Similarly, the economic growth of trading partners boosts LCT flows. The findings highlight that sustained domestic and regional growth, coupled with proactive economic and trade policies, is essential for resilient LCT trade and advancing environmental sustainability.

Table 5. CS-NARDL estimates

Dependent variable: $TLCT_{ij}$		
Variables	Long-run coefficient	Short-run coefficient
GDP^{+}_{it}	1.7372**	–
ΔGDP^{+}_{it}	–	0.7426*
ΔGDP^{+}_{it-1}	–	0.4029**
GDP^{-}_{it}	1.6900***	–
ΔGDP^{-}_{it}	–	0.6160***
ΔGDP^{-}_{it-1}	–	0.5019
$GDP^{+}_{j,t}$	2.0058***	–
$\Delta GDP^{+}_{j,t}$	–	0.6422**
$\Delta GDP^{+}_{j,t-1}$	–	0.1778
GDP^{-}_{jt}	0.9067*	–
ΔGDP^{-}_{jt}	–	1.9765***
ΔGDP^{-}_{jt-1}	–	2.8075
$ER^{+}_{j,t}$	−6.3108***	–
$\Delta ER^{+}_{j,t}$	–	−1.0037***
$\Delta ER^{+}_{j,t-1}$	–	−0.6519**
ER^{-}_{jt}	2.3403***	–
ΔER^{-}_{jt}	–	0.8966**
ΔER^{-}_{jt-1}	–	0.3063**
$\overline{GDP}_{t}$	–	1.1941**
$\overline{ER}_{t}$	–	−0.6423***
$\overline{TLCT}_{t}$	–	1.1902***
Constant	–	2.9851***
Π_{t-1}	–	−1.3228***
Model diagnostics		
Wald$_{LR}$ Asymmetry GDP$_i$	44.4779***	
Wald$_{SR}$ Asymmetry GDP$_i$	9.3210***	
Wald$_{LR}$ Asymmetry GDP$_j$	42.2779**	
Wald$_{SR}$ Asymmetry GDP$_j$	6.7974***	
Wald$_{LR}$ Asymmetry ER$_{ij}$	50.3283**	
Wald$_{SR}$ Asymmetry ER$_{ij}$	8.1833***	
Hausman test	5.8137 (0.1210)	
Observations	96	
Log likelihood	312.260	
Number of Cross Sections	4	
LM	5.3505	
F-stat	11.9447*	
R-square	0.7849	
RESET	1.241	
Residual Stationary (ADF) I(0)	2.0595*	

Note(s): *, **, *** indicates significant at 1%, 5% and 10% level of significance, respectively
Source(s): Author’s calculation using EViews

The estimates confirm a significant asymmetric effect of the carbon emissions ratio on trace in LCT. The carbon emission ratio is taken as a denominator to capture the trade barrier in the modified gravity model. CS-NARDL estimates of carbon emissions rations reveal a negative impact on TLCT in both the long run and short run. A higher carbon emissions ratio indicates that Saudi Arabia’s emissions are higher than its trading partners, reducing TLCT, making it a trade barrier posed by environmental disparities. Whereas, a lower carbon emissions ratio shows lesser carbon emissions of Saudi Arabia relative to its trading partners, facilitating

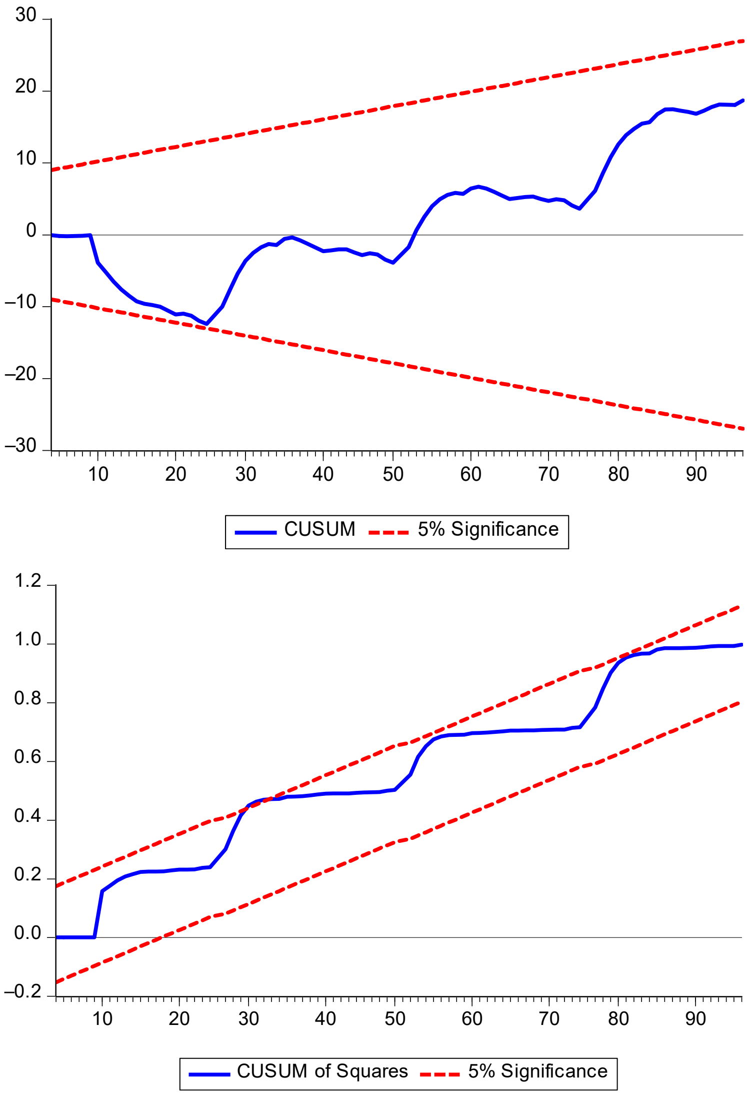

Figure 2. Cumulative sum and cumulative some of square graphs of CS-NARDL residuals. Source: Author's calculation using Eviews

greater TLCT. These findings assert the importance of reducing the emissions, which is beneficial for Saudi Arabia to increase its LCT trade. Furthermore, aligning its environmental performance with its trading partners will reduce the environmental barrier for trade and promote the diffusion of low-carbon technologies, advancing both trade and sustainability goals. The study highlights the following policy takeaways based on its findings. In line with Saudi Arabia's Vision 2030,

(1) Strategic investments in renewable energy, carbon capture and green innovation will not only advance the Kingdom's domestic sustainability targets but also strengthen its role as a regional LCT hub.

(2) At the GCC level, deeper technology partnerships with its GCC partners through synchronised emissions benchmarks, shared innovation hubs and coordinated customs facilitation can accelerate technology transfer and create a competitive regional market for sustainable technologies.

(3) Policy makers should channel investments in green and sustainable technologies to sustain economic growth and enhance LCT trade. These measures will also help diversify Saudi Arabia's economy from its traditional oil base, making trade and growth more resilient and broad-based, in line with the Vision 2030 objective of building a more diversified and competitive economy.

(4) Diversifying away from fossil fuels will ensure resilience and support environmental sustainability.

(5) Saudi Arabia should design and implement stringent environmental regulations to reduce its domestic carbon footprint, as well as that of its trading partners. This alignment will lower trade barriers and boost LCT diffusion.

The current study puts forward a novel application of the traditional gravity model to evaluate the impact of economic size (mass) and emissions ratio as a trade barrier (distance) on the bilateral flow of LCT (gravitational pull). The study also opens research possibilities to further investigate the relationship by exploring the impact of renewable energy policies, trade agreements and innovation indices in shaping trade of low carbon technology.

Author contributions
All authors contributed to the study's conception and design. Material preparation, data collection, analysis and writing final draft were performed by Dhyani Mehta.

Ethical approval
This article does not contain any studies with human participants or animals performed by any of the authors. The submitted work is original and it is not published elsewhere in any form or language. No data, text or theories by others are presented as if they were the author's own.

Data availability
The data will be made available on request from the corresponding author.

Notes

1. Oman, UAE, Kuwait, and Bahrain are included as they share borders with Saudi Arabia and are key trade partners. Meanwhile, Yemen, Iraq and Jordan are excluded due to inconsistent data availability.
2. For any variable $y_{i,t}$ $(GDP_{it}, ER_{ij,t}, TLCT_{ij,t})$, the cross-sectional average at time t is calculated as: $\overline{y_{i,t}} = \frac{1}{N}\sum_{i=1}^{N} y_{i,t}$ Where, N is total number of cross sections (countries) and Y is the values of the variable for country i for t time.

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