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Environmental Kuznets Curve dynamics in oil-rich economies

Mohammad Ridwan^{1,5}, Zulfiquar Ali Antor¹, Afsana Akther¹, Md. Emran Hossain^{2,3} and Foday Joof^{4,6*}

*Correspondence:
fjoof@cbg.gm

¹ Department of Economics,
Noakhali Science
and Technology University,
Noakhali 3814, Bangladesh

² Scientific Research Center, Baku
Engineering University, Baku,
Azerbaijan

³ Advanced Research Centre,
European University of Lefke,
TR-10 Mersin, Lefke, Northern
Cyprus, Turkey

⁴ Modeling and Forecasting Unit,
Economic Research Department,
Central Bank of The Gambia,
Ecowas Avenue, Banjul, The
Gambia

⁵ ARUCAD Research Centre,
Arkin University of Creative Arts
and Design, Northern Cyprus,
Mersin 10, Turkey

⁶ Department of Business
Administration, Faculty
of Economics, Administrative
and Social Sciences, Bahçeşehir
Cyprus University, North Cyprus,
Türkiye

Abstract

The Gulf Cooperation Council (GCC) economies, among the world's largest per-capita carbon emitters, face a pressing policy dilemma of environmental sustainability. The conventional mean-based studies often mask heterogeneous effects across the emissions distribution and yield inconclusive results for resource-rich, energy-intensive settings such as the GCC. This gap limits the design of targeted decarbonization strategies aligned with national visions (e.g., Saudi Vision 2030 and UAE Net Zero 2050). Hence, this study revisits the Environmental Kuznets Curve (EKC) hypothesis for the six GCC countries over 2000–2024 using annual panel data. This study applies quantile regression to capture distribution-specific impacts of economic growth, trade openness, energy use, and urban population on carbon emissions. Results are validated through Dumitrescu-Hurlin causality tests and robustness checks. Findings consistently reject the EKC: economic growth exerts a monotonic positive effect on carbon emissions with no turning point. Energy efficiency and renewable adoption mitigate emissions, while trade openness and technological diffusion also exert reducing effects. In contrast, urbanization significantly amplifies emissions, highlighting demographic pressures. The results underscore that environmental improvements in the GCC require deliberate structural shifts in energy diversification, urban planning, and trade policies rather than growth alone. These context-specific insights advance the environmental economics literature and offer actionable guidance for sustainable development in resource-dependent economies.

Keywords: Environmental Kuznets Curve, Carbon emissions, Economic growth, Energy use, GCC economies

1 Introduction

Carbon dioxide (CO₂) emissions remain the primary driver of global climate change, posing severe threats to environmental and economic sustainability [58, 59]. The Environmental Kuznets Curve (EKC) hypothesis, one of the most widely examined frameworks in environmental economics, posits that pollution initially rises with economic growth but eventually declines after reaching a specific income threshold [10, 36]. While extensively tested in both developed and emerging economies, the validity of the EKC remains highly questionable for the “Gulf Cooperation Council (GCC) countries. These economies are major contributors to regional energy-related pollution, with 34% of emissions originating from carbon-intensive industries such as steel, iron, cement,



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aluminum manufacturing, and construction [6]. Characterized by heavy dependence on hydrocarbons, rapid urbanization, exceptionally high per-capita energy consumption, and ambitious renewable energy initiatives, the GCC represents a distinctive high-income yet carbon-intensive context [53]. In such settings, the income level at which an EKC turning point might occur is likely to differ significantly from that of other economies. This study addresses this critical gap by providing new empirical evidence on how economic growth, energy consumption, trade openness, and urbanization interact to shape environmental performance in the GCC, thereby offering region-specific policy insights for sustainable development.

The GCC countries, Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, remain heavily reliant on hydrocarbon exports. However, domestic natural gas consumption and high energy intensity serve as the primary sources for electricity generation, water desalination, and industrial applications, creating a central energy–environment trade-off in the region [1]. Energy consumption is widely recognized in the literature as a key determinant of environmental quality [29]. In response, GCC member states have adopted ambitious efficiency targets: Saudi Arabia aimed to reduce electricity consumption by 8% by 2021, the UAE targeted a 30% cut by 2030, and Kuwait planned efficiency gains of 5% and 15% by 2020 and 2030, respectively [68]. While the continued reliance on fossil fuels drives rising emissions, the adoption of cleaner sources, including nuclear power, renewable energy, and information and communication technology (ICT), offers a promising decarbonization pathway [3, 17]. Nevertheless, rapid growth in the industrial and services sector GDP frequently offsets these environmental gains [30, 52].

Although the GCC countries are signatories to the Paris Agreement and have committed to pursuing green growth and achieving net-zero emissions [41], their economies remain heavily dependent on fossil fuel exports. According to GCC-STAT [37], oil exports accounted for 30–54% of GDP in five of the six GCC countries in 2022, with Bahrain being the exception at 17%. The literature presents mixed evidence on the trade–environment nexus. Some studies support the pollution haven hypothesis, showing that trade and industrial expansion intensify environmental degradation [11, 21]. Others demonstrate that, under specific conditions, trade can improve environmental quality through technological innovation, economic diversification, and greater renewable energy adoption [26, 64]. In response, GCC nations have actively pursued economic diversification strategies and recorded notable progress [2]. At the same time, rapid population growth and urbanization further complicate the growth–emission relationship by increasing energy demand and reliance on polluting fuels, thereby exacerbating carbon emissions [7, 25].

Despite extensive empirical research on the EKC, significant gaps persist. Inconsistent findings across studies continue to raise doubts about the hypothesis’s applicability in diverse institutional and structural contexts. In particular, the GCC economies remain severely under-researched. These high-income, hydrocarbon-dependent nations exhibit some of the world’s highest per capita CO₂ emissions, yet they are simultaneously pursuing aggressive economic diversification and carbon-neutrality targets. To address these gaps, the present study pursues three main objectives. First, it examines the relationship between economic growth and CO₂ emissions in the GCC to determine whether

the EKC hypothesis holds in high-income, fossil-fuel-reliant economies. Second, it investigates the influence of energy consumption, trade openness, and urban population on carbon emissions, taking into account the region's distinctive structural and demographic characteristics. Finally, the study aims to provide robust, evidence-based insights to support policymakers in striking an effective balance between sustained economic growth and environmental sustainability in the GCC.

This study makes four significant contributions to the environmental economics literature. First, it concentrates on the GCC economies, a region characterized by some of the world's highest per capita CO₂ emissions, heavy dependence on hydrocarbon revenues, and rapid economic diversification, yet it remains remarkably understudied within the EKC framework. Second, it employs a comprehensive set of advanced panel econometric techniques, including quantile regression along with robustness checks using Panel-Corrected Standard Errors (PCSE), Driscoll-Kraay Standard Errors (DKSE), and Generalized Least Squares (GLS) estimators. These methods overcome the methodological limitations of earlier studies that relied primarily on conventional mean-based regressions and failed to account for cross-sectional dependence, slope heterogeneity, or distributional heterogeneity. Third, by applying quantile regression, the study provides novel empirical evidence on the heterogeneous effects of economic growth, energy consumption, trade openness, and urbanization across the entire conditional distribution of carbon emissions, rather than focusing solely on average (mean) relationships. Finally, the findings deliver timely and actionable policy insights that assist GCC policymakers in striking an effective balance between ambitious economic diversification targets and long-term environmental sustainability and carbon-neutrality goals.

The rest of the paper will be structured in the following manner. Section 2 outlines the associated existing literature; Sect. 3 will include the data and variables, theoretical framework, and methods. The results and discussion are presented in Sect. 4. Policy recommendations are given at the end of Sect. 5. The final section, 6, refers to limitations and future research directions.

2 Literature review

The EKC hypothesis posits an inverted U-shaped relationship between economic growth and environmental degradation, with emissions initially rising with income before eventually declining as economies mature, adopt cleaner technologies, and implement stricter regulations. In the context of the Gulf Cooperation Council (GCC) economies, the validity of the EKC and the directional impacts of key drivers such as energy consumption, trade openness, and demographic shifts remain empirically contested. This section critically reviews the relevant literature, with particular emphasis on studies employing data from GCC countries or closely comparable oil-dependent and high-income developing economies in the MENA region. By focusing on contextually proximate research, the review highlights mixed evidence, methodological variations, and persistent gaps that motivate the present analysis of CO₂ emissions in the GCC.

2.1 GDP and carbon emission

Empirical investigations into the growth–emissions nexus in the GCC have produced heterogeneous findings, often reflecting the region's unique structural dependence on

fossil fuels. Alsamara et al. [4], applying panel data techniques including fully modified ordinary least squares (FMOLS), pooled mean group (PMG), and dynamic common correlated effects (DCCE) estimators to GCC countries over an extended period, confirm the existence of an inverted U-shaped EKC for CO₂ emissions in most member states (Qatar, Bahrain, Kuwait, Saudi Arabia, and the UAE), although the relationship does not hold for Oman. Their results suggest that economic expansion eventually exerts a mitigating effect on emissions once a certain income threshold is surpassed, consistent with the classic EKC prediction.

In contrast, Ansari et al. [9], employing dynamic ordinary least squares (DOLS) and fully modified ordinary least squares (FMOLS) on data from five GCC countries (Bahrain, Oman, Qatar, Saudi Arabia, and the UAE) spanning 1991–2017, reject the EKC hypothesis when ecological footprint is used as the environmental indicator. They find that economic growth does not exhibit the anticipated turning point; instead, it is associated with continued environmental pressure. Naz et al. [51], utilizing fuzzy-set Qualitative Comparative Analysis (fsQCA) across ASEAN economies while explicitly noting the advantages of renewable energy adoption in the GCC, similarly observe that GDP development contributes positively to ecological footprint, underscoring the scale effect of growth in resource-rich settings.

These divergent outcomes—some supporting an eventual decline in emissions with rising income and others indicating persistent or monotonic increases—highlight the sensitivity of EKC results to the choice of environmental proxy, estimation technique, and sample period. Given the GCC's ongoing diversification efforts under national visions (e.g., Saudi Vision 2030, UAE Centennial 2071), further scrutiny of the growth–emissions link using recent data remains warranted, and hence we proposed the following hypothesis:

H1: Economic growth increases CO₂ emissions in the GCC economies.

2.2 Energy use and carbon emission

Energy consumption constitutes a primary driver of emissions in energy-intensive GCC economies. Gershon et al. [38], employing static panel estimation across 24 countries from 2000 to 2022, document that energy consumption exerts a persistent positive effect on emissions, with limited mitigation potential. Methmini et al. [50], through panel regression on 20 high-emitting nations (including Saudi Arabia) over 2000–2021, likewise establish that energy use significantly elevates emissions, particularly in hydrocarbon-dependent economies.

Ben Salah et al. [18], utilizing pooled ordinary least squares (OLS) and country fixed effects (FE) panel regression models with clustered standard errors on data for all six GCC countries from 2015 to 2022, reinforce these patterns by demonstrating a robust positive association between energy consumption per capita and CO₂ emissions. Their analysis, situated in the post-Paris Agreement era, underscores that energy use remains a dominant structural driver even as GCC nations pursue diversification. Zuo and Ren [72], applying system GMM to Belt and Road Initiative (BRI) participants (including several GCC members), further show that while renewable energy adoption can curb emissions, conventional energy consumption continues to dominate the emissions profile in fossil-fuel-reliant settings. Collectively, these studies affirm that energy consumption

exerts a strong positive influence on CO₂ emissions in the GCC, consistent with the region's production structure and supporting the expectation articulated in H2.

H2: Energy consumption increases CO₂ emissions in the GCC economies.

2.3 Trade openness and carbon emission

The impact of trade openness on emissions in the GCC is theoretically ambiguous, reflecting competing scale, composition, and technique effects. Bakri et al. [13], applying threshold regression to 22 Asian nations (2000–2019), identify a non-linear pattern whereby trade openness initially raises emissions before reducing them beyond a critical threshold—broadly consistent with EKC dynamics. Ghazouani [39], employing the Method of Moments Quantile Regression (MMQR) across 26 BRI economies (2000–2020), finds that trade openness does not uniformly lower emissions but does so at higher quantiles, with fintech facilitating gradual reductions.

Focusing more directly on the GCC, Ben Salah et al. [18], in their panel analysis of the six GCC economies (2015–2022), report that trade openness is negatively associated with CO₂ emissions, attributing this to the technique effect whereby greater integration facilitates access to cleaner technologies and environmental standards. This finding aligns with the hypothesis that trade openness may ultimately exert a mitigating influence in the GCC context, although the net effect remains conditional on the level of openness and complementary policies.

H3: Trade openness decreases CO₂ emissions in the GCC economies.

2.4 Urban population and carbon emission

Rapid urbanization in the GCC, driven by population growth, infrastructure expansion, and economic diversification, has profound implications for energy demand and emissions. While earlier literature often emphasized demographic factors such as population aging in other regions, recent GCC-specific analyses directly address urban expansion. Ben Salah et al. [18], employing pooled OLS and country FE panel regressions on 2015–2022 data for the six GCC countries, provide robust evidence that urbanization positively and significantly raises CO₂ emissions per capita. Their results highlight how urban concentration amplifies energy-intensive activities, transportation, and building stock in high-income, arid environments.

This positive urbanization–emissions link is consistent with the broader pattern observed in oil-exporting economies undergoing swift urban transformation. The finding directly supports the expectation that urban population growth will increase CO₂ emissions in the GCC (H4) and underscores a gap in prior work that has under-emphasized this channel relative to energy or trade. By isolating the urban population dimension within a recent GCC panel framework, the present study contributes fresh evidence on this under-explored yet policy-relevant relationship.

H4: Urban population growth increases CO₂ emissions in the GCC economies.

2.5 Literature gap

Although prior research has examined the relationships between economic growth, energy consumption, trade openness, and urbanization on carbon emissions, the evidence for the GCC economies remains limited and inconclusive. Existing studies

focused on the region generally indicate that economic growth and energy consumption tend to increase emissions, while the effects of trade openness are often conditional or mixed, and urbanization exerts additional upward pressure on environmental degradation. However, these analyses typically rely on conventional mean-based estimators that fail to account for potential heterogeneity across different levels of emissions. Few studies simultaneously incorporate the full range of structural, energy-related, trade, and demographic drivers within a single unified framework applied exclusively to the GCC. Moreover, many draw on older datasets that do not fully reflect recent diversification efforts and policy shifts in the region.

This study addresses these shortcomings by concentrating solely on the six GCC economies and employing a quantile regression approach to capture distributional heterogeneity in the effects of the explanatory variables. Robustness is strengthened through the use of Driscoll–Kraay standard errors, panel-corrected standard errors (PCSE), and feasible generalized least squares (FGLS) estimators. By including a comprehensive set of variables representing economic growth (and its quadratic term), energy consumption, trade openness, and urban population, the analysis provides an integrated assessment of the interplay among these forces. In doing so, the research offers updated and methodologically rigorous insights into the growth–emissions nexus in hydrocarbon-dependent economies and generates policy-relevant findings for sustainable development in the GCC.

3 Data and methodology

3.1 Data description

Table 1 provides a summary of the variables employed in this study. The dependent variable representing environmental deterioration is carbon emissions (LCO₂) measured in total metric tonnes of CO₂ equivalent. GDP indicates economic growth in constant 2015 US dollars (LGDP), whereas the square of GDP (LGDP²) is utilized to illustrate the potential for a non-linear EKC. Energy consumption (LEU), measured in kgs of oil equivalent per capita, signifies the GCC’s reliance on fossil fuels, while trade openness (LTOP) and urban population (LUP) serve as measures of globalization and demographic trends, respectively.

Table 1 Data description

Variable/symbol	Description	Unit of measure	Source
LCO ₂	Carbon emission	Total (Mt CO2e)	World Development Indicator (WDI, 2024)
LGDP	Gross domestic product	Constant 2015 US\$	
LEU	Energy Use	kg of oil equivalent per capita	Computed by the authors
LTOP	Trade Openness	% of GDP	
LUP	Urban Population	% of total population	
LGDP ²	GDP squared	Derived from LGDP	
List of countries: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates			
Time period: 2000–2024			

All variables are expressed in natural logarithms. LGDP² is computed as the square of LGDP to test the nonlinear EKC relationship. Data on LGDP, LEU, LTOP, and LUP are retrieved from the World Development Indicators [69]: <https://databank.worldbank.org/source/world-development-indicators>

The upper panel of Fig. 1 presents country-level CO₂ emission trends across GCC economies over 2000–2024, revealing heterogeneous but consistently upward trajectories; Saudi Arabia records the highest absolute emission levels, while Qatar exhibits the steepest growth rate, reflecting its rapid hydrocarbon-driven economic expansion over the period. The lower panel of Fig. 1 shows the economic growth of GCC regions. All economies display a clear upward trajectory, reflecting sustained output expansion driven by hydrocarbon revenues and structural reforms, with the post-2020 segment incorporating forward projections. Qatar exhibits the most rapid early acceleration, particularly between 2000 and 2015, consistent with its LNG sector expansion, followed by stabilization at a high level. Saudi Arabia maintains the highest absolute values throughout, supported by its economic scale and Vision 2030 diversification initiatives, whereas Kuwait records initial gains that flatten after 2010. The UAE, Oman, and Bahrain show steady, moderate increases, with the UAE tracking closely behind Saudi Arabia.

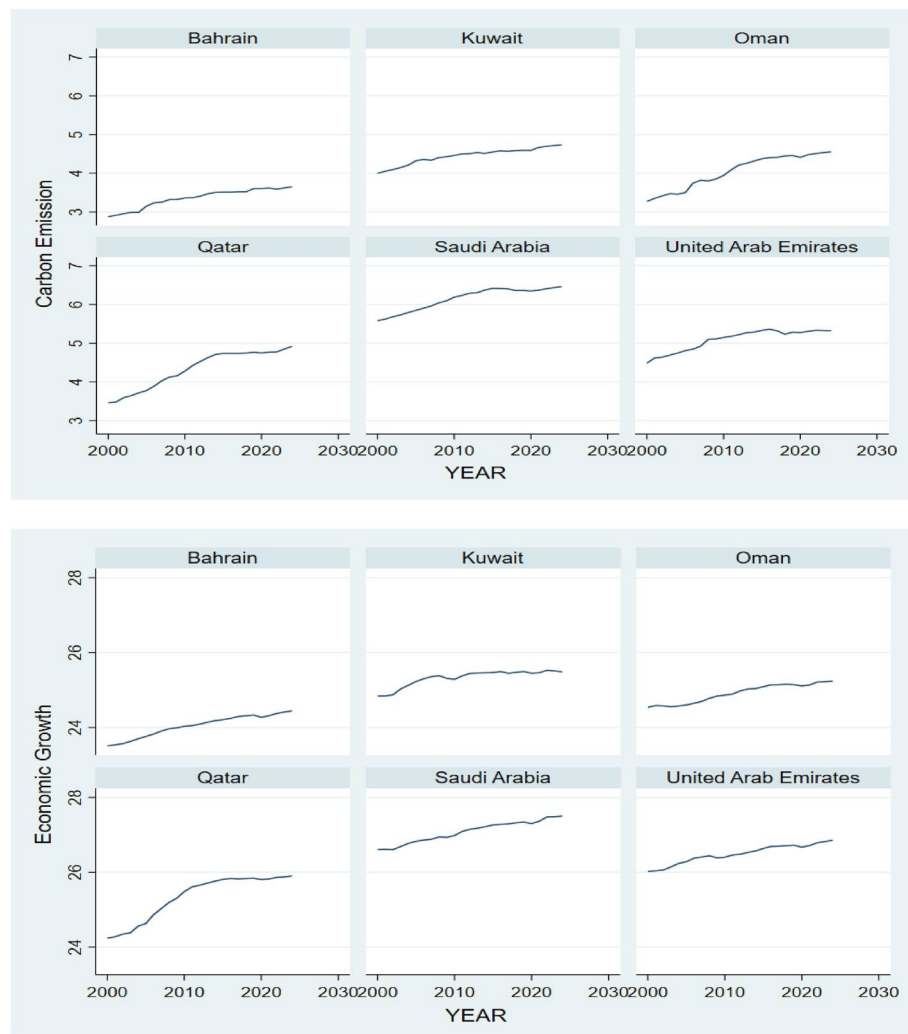


Fig. 1 Country-level trends in CO₂ emissions and economic growth for GCC Economies, 2000–2024. Notes: All values are log-transformed

Table 2 Descriptive statistics

Variable	Obs	Mean	Std. dev	Min	Max
LCO ₂	150	4.567	.938	2.878	6.462
LGDP	150	25.531	1.058	23.508	27.503
LGDP ²	150	652.928	54.167	552.638	756.399
LEU	150	9.141	.389	8.098	9.978
LTOP	150	4.634	.306	3.861	5.374
LUP	150	4.482	.096	4.27	4.605

Table 3 Pairwise correlation

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) LCO ₂	1.000					
(2) LGDP	0.977	1.000				
(3) LGDP ²	0.978	1.000	1.000			
(4) LEU	−0.198	−0.182	−0.183	1.000		
(5) LTOP	−0.395	−0.318	−0.317	0.196	1.000	
(6) LUP	−0.127	−0.155	−0.161	0.754	0.068	1.000

Table 2 indicates that the descriptive statistics of emissions in the GCC are notably elevated, with an average logged value of 4.57, exhibiting considerable variation among countries and years. The GDP has significant concentration within a substantial range (23.5–27.5 on a logarithmic scale), underscoring the disparity in economic magnitude. Energy consumption remains consistently elevated with few fluctuations (mean 9.14, standard deviation 0.39). The average level of trade openness is 4.63, exhibiting significant dispersion, which reflects diverse integration into global markets. The urbanization rate is significantly elevated, with the majority of GCC nations exhibiting an urban population over 90%. These results substantiate the carbon-intensive, trade-oriented, and highly urbanized structure of the region, which serves as a critical site for evaluating the EKC hypothesis.

Table 3 presents the correlation matrix results. The connection between carbon emissions and GDP (0.98) and GDP² (0.98) is both positive and significant, aligning with the Environmental Kuznets Curve hypothesis, which posits that environmental pressure is driven by growth in the early stages. The utilization of energy exhibits a weak negative association with both emissions and GDP, potentially signifying enhancements in efficiency or structural changes within the GCC. Emissions have a negative correlation with trade openness (−0.395), suggesting that openness may mitigate rather than exacerbate environmental stress through enhanced technology transfer. Urbanization exhibits a minor correlation with emissions but a strong relationship with energy consumption (0.75), exemplifying its indirect impact on the development of the growth-emission nexus.

3.2 Theoretical framework and hypotheses

3.2.1 The environmental Kuznets Curve

The EKC hypothesis, originally developed by Grossman and Krueger [40] and later systematised by Dinda [32], posits that the relationship between economic growth and environmental degradation follows an inverted U-shaped trajectory. In the early stages of development, rising income levels drive industrial expansion and heightened energy dependence, resulting in increased pollution. Beyond a critical income threshold, however, further economic growth tends to improve environmental quality through technological innovation, stronger regulatory frameworks, and structural shifts toward cleaner service-based sectors. The GCC context challenges this canonical path: these are already high-income economies with exceptionally high per-capita energy consumption and structural dependence on hydrocarbons, suggesting that a conventional EKC turning point may not emerge spontaneously. The general functional form of the EKC relationship is expressed as:

$$CO_2 = f(GDP, GDP^2, EU, TOP, UP) \quad (1)$$

where CO_2 denotes carbon dioxide emissions, GDP represents economic growth, while GDP^2 captures its nonlinear effect, EU denotes energy use, TOP reflects trade openness, and UP stands for urban population. To allow elasticity interpretation and to reduce heteroscedasticity, the model is expressed in log-linear form:

$$LCO_{2it} = \beta_0 + \beta_1 LGDP_{it} + \beta_2 LGDP_{it}^2 + \beta_3 LEU_{it} + \beta_4 LTOP_{it} + \beta_5 LUP_{it} + \varepsilon_{it} \quad (2)$$

A confirmed EKC requires $\beta_1 > 0$ and $\beta_2 < 0$, yielding an inverted U-shaped relationship between income and emissions. Under this condition, the income turning point is derived as:

$$GDP^* = \exp(-\beta_1/2\beta_2) \quad (3)$$

The absence of this pattern, particularly a positive β_2 , constitutes a rejection of the EKC hypothesis. In the GCC context, where structural hydrocarbon dependence persists alongside ambitious diversification targets, the sign and significance of β_2 represent the central empirical focus of this study.

3.2.2 Theoretical linkages and hypotheses

Each explanatory variable is linked to environmental outcomes through distinct theoretical mechanisms. Economic growth influences emissions through the scale effect during the early stages of development, as expanding economic activity increases energy demand and environmental pressure. At higher income levels, however, technique and composition effects may reduce emissions as economies adopt cleaner technologies, strengthen environmental regulations, and shift toward less carbon-intensive sectors [8, 63]. Whether such a transition occurs in GCC economies remains a central focus of this study.

Energy consumption is a key driver of CO_2 emissions in fossil-fuel-dependent economies, where electricity generation, desalination, and industrial activities rely heavily

on hydrocarbons. Nevertheless, improvements in energy efficiency and the adoption of renewable energy sources may weaken this relationship and support the downward phase of the Environmental Kuznets Curve (EKC) [5].

Trade openness affects environmental quality through competing channels. The pollution haven hypothesis suggests that trade liberalization may increase emissions by encouraging the relocation of pollution-intensive industries to countries with less stringent environmental regulations. In contrast, the technique effect argues that openness facilitates the transfer of cleaner technologies and more efficient production practices, thereby reducing emissions over time [28, 62]. The overall impact is therefore an empirical matter.

Urbanization can increase emissions by raising energy demand, transportation needs, and infrastructure expansion during the early stages of urban growth. However, at more advanced stages, greater population density, improved energy efficiency, and investments in sustainable infrastructure may mitigate environmental pressures [27, 66]. Given the rapid population growth and urban expansion observed in the GCC, urbanization is expected to remain an emission-enhancing factor.

Drawing on these theoretical arguments, Fig. 2 presents the conceptual framework illustrating the proposed theoretical linkages among the study variables and the EKC testing mechanism.

3.3 Econometric approach

The study was carried out using a sequential econometric approach to rigorously study the relationship between growth and emissions. Firstly, the cross-sectional dependence has been checked through the Pesaran [55] CD test, which determines whether unobserved common shocks or spillovers occur among several units. Such dependence should be taken into consideration to prevent biased inference in regional panel data. Slope homogeneity was then analyzed by the test suggested by Pesaran and Yamagata [57], which deduces the presence of country-level specific slope heterogeneity and whether it needs to be included in the estimation plan. The panel unit root test by Levin et al. [46] and the ADF test by Dickey and Fuller [31] were used to ensure stationarity. Moreover, the cross-sectionally augmented IPS (CIPS) test by Pesaran [56] was used to correct possible cross-sectional dependence.

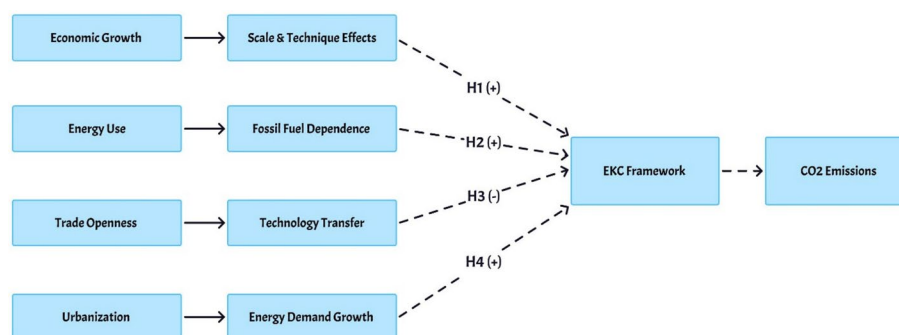


Fig. 2 Conceptual framework of the study

Table 4 CSD test

Variable	CD-stat	P-value
LCO ₂	18.934	0.000***
LGDP	18.465	0.000***
LGDP ²	18.465	0.000***
LEU	−1.427	0.153
LTOP	6.864	0.000***
LUP	14.502	0.000***

*** p < 0.01

Table 5 Slope homogeneity test

	Delta	P-value
Delta	7.872***	0.000
Adj. delta	9.278***	0.000

*** p < 0.01

Lastly, long-run relationships were investigated by applying the Pedroni [54] panel cointegration test, which accommodates heterogeneity in cointegrating vectors and offers both within-dimension (panel) and between-dimension (group) statistics. This test is particularly suited to the present dataset, given the confirmed slope heterogeneity across GCC countries (Table 5) and the presence of cross-sectional dependence (Table 4). The test is applied both without and with a deterministic trend; the trend specification is justified on economic grounds — the GCC economies underwent persistent structural transformation over 2000–2024 through progressive integration into global energy markets, demographic expansion, and phased renewable energy adoption, generating a deterministic upward trend in emissions that is independent of the explanatory variables. Omitting this trend would introduce omitted-variable bias, inflating the estimated coefficients on GDP and urbanization. The stronger and more consistent cointegration evidence in the with-trend specification (Table 7) further corroborates this choice.

To conduct the main analysis, the study used quantile regression by Koenker and Bassett [44] that can explain distributional heterogeneity in carbon emissions. Quantile regression is not like ordinary least squares in that it does not estimate the average effect of explanatory variables, but instead it enables estimation of relationships at various points of the emissions distribution, which spans variations between low-, median-, and high-emission observations [43]. This method can be effective in showing how economic growth, energy consumption, openness to trade, and urbanization affect countries in different ways depending on their level of emission [45]. Moreover, this method allows a more detailed view of growth-environment relationships and indicates heterogeneity that standard measure-based models may fail to capture.

Formally, the conditional quantile function is expressed in Eq. (4):

$$Q_{CO_2it}(\tau|X_{it}) = \alpha_{i(\tau)} + X'_{it}\beta(\tau), 0 < \tau < 1 \quad (4)$$

where $Q_{CO_2_{it}}(\tau|X_{it})$ denotes the τ -th conditional quantile of carbon emissions, $\alpha_{i(\tau)}$ captures country fixed effects, and $\beta(\tau)$ represents the vector of slope parameters that vary across quantiles.

The estimation is obtained by solving the minimization problem given in Eq. (5):

$$\hat{\beta}(\tau) = \operatorname{argmin}_{\beta} \sum_{i=1}^N \sum_{t=1}^T \rho_{\tau} \left(CO_{2it} - \alpha_{i(\tau)} - X'_{it} \beta(\tau) \right) \quad (5)$$

where $\rho_{\tau}(\mu) = \mu(\tau - I\{\mu < 0\})$ is the quantile loss function.

Once the quantile regression analysis was done, the study proceeded with the causal relationship analysis by Dumitrescu and Hurlin's [34] panel Granger causality test. This test takes into account the heterogeneity across different countries but offers the overall panel-level inference. In order to be certain about the strength of the results, several estimators were used, such as the PCSE, DKSE, and GLS estimators. Heteroscedasticity and contemporaneous panel-to-panel correlation were corrected using Panel-Corrected Standard Errors (PCSEs, [16]). Potential cross-sectional dependence and serial correlation were corrected using Driscoll-Kraay standard errors [33], and Generalized Least Squares [12] was used to offer efficient estimates in case of heteroscedasticity and correlated errors. A combination of these assures the fact that the results are uniform, reliable, and not methodologically motivated.

4 Results and discussions

4.1 CSD results

Table 4 demonstrates that most variables exhibit a significant degree of cross-sectional dependence. For instance, carbon emissions (LCO₂) exhibit a CD-statistic of 18.934 ($p < 0.01$), GDP (LGDP) shows 18.465 ($p < 0.01$), and urban population (LUP) presents 14.502 ($p < 0.01$). There exists a significant reliance on trade openness (LTOP) (6.864, $p < 0.01$). All exclusions are to energy use (LEU), which exhibits a non-significant statistic 1.427, $p = 0.153$). The findings indicate a significant interconnection between CO₂ emissions and most explanatory variables across the GCC nations, underscoring the need for econometric methodologies that particularly account for cross-sectional correlation.

4.2 Slope homogeneity test

According to Table 5, the null hypothesis about the homogeneity of slope is rejected, with delta statistics of 7.872 ($p < 0.01$) and adjusted statistics of 9.278 ($p < 0.01$). This demonstrates the variation in slope coefficients among the GCC economies, indicating that the impact of GDP, energy consumption, trade openness, and urbanization on emissions significantly differs among the nations. Consequently, pooling models are insufficient in this instance; rather, heterogeneous panel estimators are appropriate.

4.3 Unit-root test

Table 6 presents the stationarity properties of the study variables. The results indicate that CO₂ emissions (LCO₂) are stationary at the level, implying integration of order zero [I(0)]. In contrast, GDP (LGDP), GDP squared (LGDP²), energy consumption (LEU), trade openness (LTOP), and urban population (LUP) are non-stationary at the level but become stationary after first differencing, indicating integration of order one [I(1)]. The

Table 6 Stationary test (LLC, CIPS, and ADF)

Variable	LLC		CIPS		ADF		
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	Order
LCO ₂	−5.4151***	−5.8531***	−2.266***	−4.527***	19.2129*	32.8853***	I(0)
LGDP	−4.6077***	−7.0269***	−2.080	−3.250***	19.3092*	51.0033***	I(1)
LGDP ²	−4.5114***	−7.0993***	−2.082	−3.214***	18.6119*	51.9630***	I(1)
LEU	−5.4549***	−9.7064***	−2.062	−5.295***	18.4977	66.2870***	I(1)
LTOP	−4.1085**	−9.4556***	−1.867	−4.198***	23.4833**	65.6962***	I(1)
LUP	−2.3655	−5.1022***	−3.343***	−3.134***	22.5169**	29.3813***	I(1)

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$ **Table 7** Cointegration results

	Without trend		With trend	
	Statistic	p-value	Statistic	p-value
Modified Phillips-Perron t	2.6801	0.0037	2.4155	0.0079
Phillips-Perron t	0.8084	0.2094	−2.2160	0.0133
Augmented Dickey-Fuller t	0.5231	0.3005	−2.1750	0.0148

presence of mixed orders of integration, with LCO₂ classified as I(0) and the remaining variables as I(1), necessitates careful consideration regarding the appropriate estimation strategy.

Estimating the model in first differences would remove the long-run information that is central to testing the EKC hypothesis. Therefore, estimation in levels is preferred when a stable long-run relationship exists among the variables. According to the cointegration literature, OLS-based estimators applied to level-form equations yield super-consistent estimates in the presence of cointegration, rendering differences in integration orders less problematic for long-run inference [35, 54]. Moreover, the quantile regression approach employed in this study focuses on the conditional distribution of the dependent variable rather than conventional moment-based estimation and does not require all variables to possess the same order of integration. Taken together, these considerations justify proceeding with panel cointegration testing and the subsequent estimation of the model in levels to capture the long-run relationships among the variables.

4.4 Pedroni cointegration test

Table 7 reports the Pedroni cointegration test results, which provide evidence of a long-run equilibrium relationship among the variables. The Modified Phillips–Perron (PP) t-statistic is statistically significant both without a deterministic trend (2.68, $p = 0.004$) and with a trend (2.42, $p = 0.008$), offering strong support for cointegration. Although the Augmented Dickey–Fuller (ADF) statistic is insignificant in the specification without a trend (0.52, $p = 0.301$), it becomes significant when a deterministic trend is incorporated (−2.175, $p = 0.015$). A similar pattern emerges for the Phillips–Perron t-statistic, which is also significant in the trend specification (−2.216, $p = 0.013$).

Overall, the results provide robust evidence of a stable long-run relationship among carbon emissions, economic growth, energy consumption, trade openness, and

urbanization in the GCC countries. The stronger and more consistent evidence obtained from the trend specification suggests that the long-run relationship is better characterized by a deterministic trend, reflecting the substantial economic, demographic, and structural changes experienced by GCC economies during the study period. These findings support the existence of cointegration among the variables, thereby justifying the estimation of the model in levels and providing an appropriate framework for examining the long-run validity of the EKC hypothesis. Although the Westerlund [67] error-correction-based cointegration test could be employed as an additional robustness check due to its ability to account for cross-sectional dependence through bootstrapped critical values, the Pedroni test remains suitable given the relatively small panel dimension ($N=6$, $T=25$) and offers sufficiently robust evidence of long-run equilibrium relationships among the variables.

4.5 Quantile regression results

Table 8 reports the quantile regression results. The coefficient of GDP (LGDP) is negative across all quantiles, ranging from -5.182 at the 5th percentile to -2.546 at the 75th percentile and -3.140 at the 90th percentile. However, the coefficient of the squared GDP term ($LGDP^2$) remains positive and statistically significant throughout the distribution. Taken together, these results indicate a U-shaped rather than an inverted U-shaped relationship between economic growth and CO_2 emissions in the GCC countries, thereby rejecting the EKC hypothesis. This finding suggests that economic growth in the GCC continues to be associated with rising emissions, implying that the benefits of growth have not been accompanied by corresponding environmental improvements. The results are consistent with evidence from fossil fuel-dependent economies, where growth–emissions dynamics often follow monotonic or N-shaped patterns rather than the conventional EKC trajectory [20, 49]. The continued dependence of GCC economies on hydrocarbons, energy-intensive industries, rapid urbanization, and large-scale infrastructure development has sustained high energy demand and carbon emissions. In addition, limited structural diversification and the relatively slow adoption of renewable energy technologies have constrained the decoupling of economic growth from environmental degradation. Similar positive growth–emissions relationships have been

Table 8 Quantile regression findings

Variable	Q(.05)	Q(.25)	Q(.50)	Q(.75)	Q(.90)
LGDP	-5.182011^{***} (.753086)	-3.856959^{***} (1.011608)	-3.116387^{***} (.813478)	-2.545642^{***} (.6745972)	-3.139788^{***} (.3704422)
$LGDP^2$	$.1179548^{***}$ (.014726)	$.0918406^{***}$ (.0197812)	$.0770218^{***}$ (.0159069)	$.0661527^{***}$ (.0131912)	$.0782748^{***}$ (.0072437)
LEU	$-.1395897^{**}$ (.062664)	$-.1850865^{**}$ (.0841755)	$-.2404733^{***}$ (.0676892)	$-.2750582^{***}$ (.056133)	$-.3114641^{***}$ (.0308244)
LTOP	$-.2626228^{***}$ (.053048)	$-.2394517^{***}$ (.0712586)	$-.2555057^{***}$ (.0573021)	$-.2156644^{***}$ (.0475192)	$-.1759188^{***}$ (.0260943)
LUP	1.902203^{***} (.2634224)	1.731564^{***} (.353851)	$.8206971^{***}$ (.2845469)	$.5517355^{**}$ (.2359677)	$.6935322^{***}$ (.1295772)
_Cons	53.59678^{***} (9.33408)	37.98879^{***} (12.53832)	33.5658^{***} (10.0826)	27.51487^{***} (8.361255)	34.34264^{***} (4.591424)

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Values in parentheses denote standard errors

documented in previous studies, including Balza et al. [14], Caporale et al. [19], and Mahajan and Sah [47], who report that economic expansion remains a significant driver of CO₂ emissions in both emerging and resource-dependent economies.

The positive coefficient on the squared GDP term (LGDP²), which ranges from 0.118 at the 5th quantile to 0.066 at the 75th quantile, further reinforces the rejection of the EKC hypothesis. Rather than identifying a turning point at which higher income levels lead to environmental improvements, the results indicate that rising income continues to exert upward pressure on emissions across the entire distribution. The absence of a meaningful turning point suggests that economic growth alone has not generated the structural transformation, technological progress, or energy transition necessary to reduce environmental degradation in the GCC. Unlike many OECD and advanced Asian economies, where emissions tend to decline after surpassing a certain income threshold, the GCC countries have yet to reach a stage where higher income translates into lower environmental pressure [15, 65]. Consequently, the findings imply that targeted environmental policies, energy diversification, and greater investment in low-carbon technologies are required to decouple economic growth from CO₂ emissions in the region.

To further substantiate the EKC rejection, Table 9 reports the theoretical income turning points and quantile-specific marginal effects of GDP on CO₂ emissions. Across all quantiles, the implied turning points range from $\ln(\text{GDP}^*) = 19.24$ at Q0.75 to $\ln(\text{GDP}^*) = 21.97$ at Q0.05, corresponding to income levels between USD 2.27×10^8 and USD 3.47×10^9 . These values lie substantially below the observed sample minimum of LGDP = 23.508, meaning the theoretical turning point falls entirely outside the range of income levels observed in the GCC over 2000–2024. This confirms that no EKC turning point is attained within the sample, and that emissions continue to rise monotonically with income throughout the observed income range. The marginal effects are uniformly positive across all quantiles. At the sample mean (LGDP = 25.531), a 1% increase in GDP raises CO₂ emissions by approximately 0.82–0.86% depending on the quantile, with the effect slightly stronger at higher emission quantiles (Q0.90: 0.857) than at lower ones (Q0.50: 0.817). At the sample maximum (LGDP = 27.503), the marginal effect rises to approximately 1.09–1.31%, indicating that the growth–emission relationship actually intensifies at higher income levels within the GCC context. Collectively, the turning point analysis and marginal effects provide systematic quantitative evidence that economic growth in the GCC exerts a persistent, distribution-wide, and intensifying

Table 9 EKC turning points and marginal effects of GDP on CO₂ emissions

Quantile	β_1 (LGDP)	β_2 (LGDP ²)	$\ln(\text{GDP}^*)$	GDP* (USD)	ME at min	ME at mean	ME at max
Q0.05	−5.182***	0.118***	21.97	3.47×10^9	0.364	0.841	1.306
Q0.25	−3.857***	0.092***	20.99	1.32×10^9	0.461	0.833	1.195
Q0.50	−3.116***	0.077***	20.23	6.11×10^8	0.505	0.817	1.120
Q0.75	−2.546***	0.066***	19.24	2.27×10^8	0.565	0.832	1.093
Q0.90	−3.140***	0.078***	20.06	5.13×10^8	0.540	0.857	1.166
PCSE/DKSE/GLS	−3.830***	0.091***	20.96	1.27×10^9	0.465	0.835	1.196

GDP* = $\exp(-\beta_1 / 2\beta_2)$ is the theoretical EKC income turning point expressed in constant 2015 USD. ME = marginal effect = $\beta_1 + 2\beta_2 \cdot \text{LGDP}$, evaluated at the sample minimum (LGDP = 23.508), mean (LGDP = 25.531), and maximum (LGDP = 27.503). All theoretical turning points fall below the lower bound of the observed sample range (LGDP = 23.508–27.503), confirming that the EKC turning point is not attained within the GCC panel. *** p < 0.01

positive effect on CO₂ emissions, with no prospect of an automatic EKC-type reversal within the foreseeable income range.

Energy use (LEU) exhibits negative coefficients that become increasingly negative, from 0.14 at the 5th percentile to 0.31 at the 90th percentile, suggesting that efficiency improvements or the adoption of renewable energy may more effectively mitigate emission increases as the level of emissions rises. The negative sign of the energy use coefficient across all quantiles indicates that, in the current specification, Hypothesis H2 is rejected: energy use does not exert the anticipated positive effect on CO₂ emissions in the GCC over the sample period. Surprisingly, there are also mitigating impacts of energy consumption on emissions, although probably through efficiency improvements, the move to renewable energy, and a slow shift in the energy mix. This is consistent with evidence elsewhere in the world that energy efficiency and digitalization have the potential to cut emissions [60, 61, 72], but it is incompatible with results in other regions, such as Sub-Saharan Africa and China, where energy consumption remains a leading contributor to emissions [38], Zhao et al., 2025).

Trade openness (LTOP) correlates with a consistent reduction in emissions, and the coefficients ranging from 0.26 to 0.18 indicate that cleaner production has been facilitated by integration with global markets across various quantiles. The GCC trade openness seems to lower emissions, and this is an indication that globalization enables the transfer of cleaner technologies and environmentally friendly practices, and not pollution havens. This highlights the significance of institutions and technological systems in ensuring that trade is environmentally friendly [42, 64]. Nevertheless, such a trend is a contrast to certain Asian and developing economies, which traditionally have witnessed expansion of trade, which has raised emissions because of the scale effects [13, 71]. This conclusion contrasts with those of the OECD and other affluent countries, which have shown inverted U-shaped curves [48]. The GCC example illustrates the limiting impact of structural dependence on hydrocarbons on reaching the EKC turning point in the foreseeable future.

In contrast, urbanization (LUP) exerts a beneficial effect, most pronounced at lower quantiles (1.90 at Q0.05), diminishing at higher quantiles (0.55 at Q0.75). Overall, the quantile regression demonstrates that the EKC is absent in the GCC; instead, emissions escalate with expansion, while trade and energy efficiency only partially alleviate the issue. The increased concentration of people in cities leads to increased energy use and transport-associated emissions, which also follow the trend of other rapidly expanding economies, such as China [22–24], Quan et al., 2025). In contrast to studies indicating long-term mitigation through effective urban systems [70], the evidence from the GCC implies that urbanization contributes to environmental stress rather than serving as a means of decoupling. In contrast to other areas, where urban planning and infrastructural growth have alleviated the effects of emissions, the GCC experience indicates that urban growth continues as a significant source of environmental stress.

In general, the findings indicate that GCC countries cannot use economic growth as the sole tool that would ensure the process of environmental improvement. Although energy efficiency and trade openness provide some relief, GDP growth remains the overriding factor in emissions. This result is contrary to OECD and other high-income countries, where the inverted U-shaped EKCs are used to indicate the constraining nature

of hydrocarbon dependence. The research has added to the literature by proving that the dynamics of EKC cannot be applied in universal contexts but instead depend on the energy systems, trade policies, and patterns of urbanization.

4.6 Dumitrescu-hurlin causality findings

Table 10 reports the results of the Dumitrescu-Hurlin (2012) panel causality test, which provides critical insights into the directional relationships among the variables. The analysis reveals a strong bidirectional causality between economic growth (GDP) and carbon emissions. Specifically, carbon emissions Granger-cause GDP ($W\text{-stat} = 2.82$, $p = 0.0016$), while GDP also Granger-causes carbon emissions ($W\text{-stat} = 3.17$, $p = 0.0002$). An identical bidirectional pattern is observed between GDP² and carbon emissions, reinforcing the mutual reinforcement between growth and environmental degradation. Energy consumption further exhibits unidirectional Granger causality toward carbon emissions ($W\text{-stat} = 3.50$, $p < 0.01$). Urbanization stands out as the most powerful driver, displaying exceptionally strong unidirectional causality from urban population to CO₂ emissions ($W\text{-stat} = 72.75$, $Z\text{-bar} = 124.27$). This highlights the dominant role of rapid demographic and spatial transformation in intensifying emissions within the GCC region. In contrast, trade openness does not Granger-cause carbon emissions ($p = 0.39$). However, a unidirectional causality runs from carbon emissions to trade openness ($W\text{-stat} = 3.01$, $p = 0.0005$), suggesting that higher emission levels may influence trade patterns and openness.

Collectively, these results underscore a self-reinforcing feedback loop between economic expansion and environmental degradation in the GCC economies. The absence of any evidence of a self-correcting mechanism provides additional empirical support for the rejection of the EKC hypothesis in this high-income, hydrocarbon-dependent context.

4.7 Robustness check

To validate the reliability of the primary findings, additional robustness checks were conducted using three alternative panel estimation techniques. The results, presented in Table 11, strongly confirm the persistent absence of an EKC relationship in the GCC economies. Across all three estimators, PCSE, DKSE, and GLS, the coefficient on GDP

Table 10 Causality test

Directions	w-stat	z-bar	P-value
LCO ₂ → LGDP	2.8246	3.1604	0.0016***
LCO ₂ → LGDP ²	2.7066	2.9559	0.0031***
LCO ₂ → LEU	1.5959	1.0321	0.3020
LCO ₂ → LTOP	3.0133	3.4872	0.0005***
LCO ₂ → LUP	2.3320	2.3072	0.0210**
LGDP → LCO ₂	3.1689	3.7567	0.0002***
LGDP ² → LCO ₂	3.1269	3.6839	0.0002***
LEU → LCO ₂	3.4953	4.3220	0.0000***
LTOP → LCO ₂	1.4918	0.8519	0.3943
LUP → LCO ₂	72.7476	124.2704	0.0000***

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

Table 11 Robustness findings

Variable	PCSEs	DKSE	GLS
LGDP	−3.830385***(.600208)	−3.830385***(.8492657)	−3.830385***(.6164582)
LGDP ²	.0913691***(.0118193)	.0913691***(.0170269)	.0913691***(.0120543)
LEU	−.2552453***(.0500953)	−.2552453***(.0283394)	−.2552453***(.0512952)
LTOP	−.2554515***(.0425355)	−.2554515***(.0421836)	−.2554515***(.0434238)
LUP	1.369402***(.2243411)	1.369402***(.2878496)	1.369402***(.2156313)
Cons	40.08098***(.746566)	40.08098***(.10.38046)	40.08098***(.7.640655)

PCSE Panel-Corrected Standard Errors, DKSE Driscoll-Kraay Standard Errors, GLS Generalized Least Squares

*** $p < 0.01$. Values in parentheses denote standard errors.

remains negative (approximately -3.83), while the coefficient on GDP² is positive (approximately 0.091) and statistically significant at the 1% level. This U-shaped pattern between economic growth and carbon emissions aligns closely with the quantile regression results, providing further evidence against the conventional inverted-U-shaped EKC hypothesis in the GCC context. Energy use continues to exert a mitigating effect on carbon emissions (coefficient ≈ -0.26). Trade openness also consistently reduces emissions, with an estimated coefficient of approximately -0.255 . In contrast, urbanization maintains a strong positive and highly significant impact on CO₂ emissions, with coefficients around 1.37 (significant at the 1% level) across all models. The high degree of consistency in the direction, magnitude, and statistical significance of the coefficients across PCSE, DKSE, and GLS estimators demonstrates that the rejection of the EKC hypothesis is not a methodological artifact. Rather, it represents a robust and reliable empirical outcome for the high-income, hydrocarbon-dependent GCC economies.

5 Conclusion and policy recommendations

5.1 Conclusion

This article has analyzed the EKC hypothesis of the GCC region based on 2000–2024 annual data. The effects of GDP, trade openness, urban population, and energy use on carbon emissions were analyzed by advanced panel econometric methodologies such as quantile regression, causality tests, and robustness checks. To test the reliability of the panel data, the study was initiated by conducting tests of cross-sectional dependence, slope heterogeneity, unit roots, and cointegration. The findings indicate that the EKC is not significant in GCC economies. The results of quantile regression show that there is a positive, monotonic relationship between economic growth and carbon emissions, and no turning point exists. The mitigating factors are the adoption of renewable energy and energy efficiency, whereas trade openness and diffusion of technology can reduce emissions. On the other hand, urbanization still accelerates emissions, which also shows the pressure on the environment posed by the rapid demographic growth. These results indicate that economic growth is not sufficient to enhance the environment, but a structural change in energy diversification, trade, and urban planning is necessary.

Moreover, the consistency of these findings was validated by robustness tests with PCSEs, Driscoll-Kraay, and GLS estimators with slight variations in the level of significance. According to the Dumitrescu-Hurlin causality test, a two-way causal relationship is observed between GDP and GDP square and urban population and carbon emission,

whereas energy use has a one-way causal relationship with CO₂ and trade openness with CO₂. There was no causal association between CO₂ and energy use or between trade openness and CO₂. These results suggest that GCC economies will not spontaneously shift to a low-emission path unless a specific policy intervention is enacted. Thus, policy interventions need to be addressed on the structural causes of emissions, such as energy diversification, sustainable trade, and environment-friendly urbanization.

5.2 Policy directions

The results present several valuable lessons to policymakers in the GCC region. The findings reveal that the EKC may not necessarily be relevant to these economies. That is, economic growth in itself will never result in a reduction in emissions. Rather, environmental pressure grows along with growth. Governments should thus be proactive in ensuring that the connection between economic growth and emissions is unraveled. It is not sufficient that technological advances occur by themselves, but active and properly developed environmental and industrial policies are required to facilitate a sustainable structural transformation. One of the greatest difficulties is in the energy sector. Despite the increasing efficiency and renewable energy initiatives, the region remains very reliant on hydrocarbons, hence unable to decouple growth and emissions. Policymakers need to accelerate the shift to clean energy, investing more in renewable energy sources (solar and hydrogen) and increasing the criterion of energy efficiency in industries, buildings, and households. The GCC economies can also be encouraged to shift towards a more sustainable and less carbon-intensive type of growth through the encouragement of regional cooperation in renewable innovation and the encouragement of low-carbon energy infrastructure.

There should be balanced strategies for trade openness and urbanization. With stringent environmental policies and green finance policies, increasing trade and investment in clean technologies could reduce emissions. The government must facilitate the transfer of technology, sustainable business operations, and the signing of international climate treaties. Meanwhile, the process of rapid urbanization keeps exerting a growing environmental pressure. Planning in the cities should thus be centered on sustainable infrastructure, energy-conserving buildings, and low-carbon transportation. The GCC countries can decrease the carbon footprint of their expanding cities by incorporating renewable energy into the urban network and providing incentives for green building. In general, the environmental objectives should be incorporated in the economic policies by enhancing the regulations, pricing carbon, and encouraging cleaner industries to achieve long-term climate sustainability and balanced development.

6 Limitations and recommendations for future research

There are some significant limitations in this study. It primarily depends on data on a national level that can mask the variation between regions, sectors, or industries. Econometric models relied upon are based on average relationships; hence, they may not fully explain the variation between countries in their response to changes in energy use, income, or policies. The research also fails to consider the possibility of structural rupture or change in policy regimes that may change the trend of emissions over time. Another challenge was that of data limitations, with some useful sources, such as

satellite-based indicators, firm-level observations, or CO₂ data specific to sectors, not being available. Such gaps could restrict the possibility of describing short-term variability or local environment impacts. Finally, the analysis assumes that the relationships between variables will stay constant, which might not be the case in the occurrence of significant global or economic shifts.

Future research must seek to enhance the methodological richness as well as the subject matter of environmental-economic research. It would be beneficial to use more sophisticated econometric models (e.g., QARDL or time-varying parameter models) to capture long-term and short-term changes in emissions. Such approaches can identify the patterns that are concealed in average-based estimates and explain more about the response of countries at various phases of development towards environmental policies. Researchers were also able to model the shifts of regimes and structural change that may enable them to understand the effects of global crises, energy reforms, or technological changes on the emission-growth relationships.

In addition to methodology, upcoming studies must be based on less aggregated and more detailed datasets, including sectoral emissions, energy consumption by fuel type, and embodied trade data. By combining econometric models with energy systems, CGE, or integrated assessment models, it is possible to design scenario-based analysis that will help policymakers to adopt balanced and evidence-based policies. Other aspects of such research must involve wider themes such as digitalization, the quality of institutions, innovation, and economic complexity to comprehend the interplay of these aspects with energy and environmental results. Lastly, there should be emphasis on transparent data reporting, open-access techniques, and reproducibility in order to provide findings that would be comparable and credible across the regions and studies.

Finally, methodological integrity and transparency should be the focus of future research. Bayesian model averaging, sensitivity analysis, and out-of-sample validation would decrease model-specific prediction; however, the prudent application of machine learning could complement econometrics with conventional forecasting and factor in variable non-significance. Well-documented data pipelines, information on data replication, and standard definitions of open data on trade and urbanization will enable comparability across jurisdictions and research studies in order to determine whether the results of identifying growth-emission relationships are structural or context-specific.

Author contributions

Mohammad Ridwan: Conceptualization, Data curation, Formal analysis, Methodology, Writing—original draft. Zulfiqar Ali Antor: Investigation, Software, Visualization, Writing—original draft. Afsana Akther: Data curation, Formal analysis, Visualization, Writing—original draft. Md. Emran Hossain: Conceptualization, Supervision, Validation, Writing—review & editing. Foday Joof: Supervision, Funding Acquisition, Writing—review & editing.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

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Consent for publication

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Competing interests

The authors report there are no competing interests to declare.

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