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Research Article

The contribution of green technological innovation, clean energy, and oil rents in improving the load capacity factor and achieving SDG13 in Saudi Arabia

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Abstract. This research aims to assess the effects of green technological innovation, renewable energy sources, and oil rents on the load capacity factor in Saudi Arabia from 1988 to 2021. The primary conclusions can be outlined as follows. The combined cointegration and Saikkonen-Lütkepohl cointegration tests reveal long-run relationships between the load capacity factor and the explanatory variables at the 1% significance level. In comparison, the Phillips-Ouliaris test shows evidence of cointegration only at 10%. Moreover, the quantile regression indicates that oil rents adversely impact environmental quality; however, they remain contingent upon environmental conditions. A 1% increase in oil rents results in a decline in environmental quality by 0.025% under poor conditions, 0.036% under moderate/normal conditions, and 0.108% under good conditions. On the contrary, renewable energy consumption and green technological innovation improve environmental quality, irrespective of the prevailing environmental conditions. However, the environmental impacts of renewable energy consumption exceed those of green technological innovation. Results show that a 1% increase in renewable energy consumption leads to a 0.052-0.253% improvement in environmental quality, whereas a 1% increase in green technological innovation results only in a 0.017-0.047% improvement. Finally, population and GDP per capita exert negative and positive implications on the load capacity factor, respectively, while energy intensity has no significant environmental effects. The research findings provide significant insights and suggest policy recommendations to address climate change and meet the targets set out in SDG13.

Keywords: Load capacity factor; sustainable development; renewable energy; technological innovation; Saudi Arabia; Quantile regression.

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1. Introduction

A swift decline in environmental quality has marked the preceding decades. Policymakers, scholars, and international organizations have extensively debated climate change, and the level of interest in environmental issues has increased significantly over time (Uralovich *et al.,* 2023; Benhamed *et al.,* 2023). This has resulted in extensive research on factors contributing to environmental deterioration and exploring potential strategies to preserve the ecology (Acheampong and Osei Opoku, 2023). Many factors have been recognized as potential drivers of environmental deterioration, including fossil fuels, economic activity, and human capital (Ayhan *et al.,* 2023; Wang et al., 2023). Other works focused on factors leading to the preservation of the environment, including green innovation, eco-friendly technologies, and renewable energy (Ragmoun, 2024b, Zhang *et al.,* 2021).

Previous studies supported the strong correlation between various factors and environmental deterioration and their ability to affect energy use and biocapacity (Ahmed *et al.,* 2022; Bulut *et al.,* 2024). In this context, one of the significant factors that deserve attention is green technological innovation (GTI), which allows for the reduction of energy consumption in the production process (Abbasi et *al.,* 2022; Ragmoun, 2024) and the introduction of renewable energy technologies (Hossain *et al.,* 2022). A substantial body of study has also confirmed the contribution of renewable energy in reducing CO2 emissions and alleviating environmental degradation (Yadav *et al.,* 2024). In this way, technological innovation can be used to develop and implement new practices and/or ideas supporting the renewable energy industry and leading to environmental preservation (Chen *et al.,* 2023, Ragmoun, 2022). Some other investigations also treated oil rents as a major determinant of environmental quality in oil-producing countries. Al-Mulali et *al.* (2015) demonstrated that high oil rents increase CO2 emissions, while Arslan *et al.* (2022) concluded that resource rents improve environmental quality. In this research area, empirical research revealed a complex and multifaceted relationship between oil rents and environmental quality due to the presence of conflicting effects (Shittu *et al.,* 2021; Sweidan and Elbargathi, 2022; Niu *et al.,* 2023). Despite the boom of studies assessing the effects of the abovementioned factors on environmental quality, most have concentrated on developed countries and selected

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emerging countries, mainly China and India (Nuţă, *et al.,* 2024). In addition, the existing literature lacks an integrative approach to assess the combined effect of green technological innovation, oil rents, and renewable energy consumption on environmental quality in Saudi Arabia.

At the same time, indicators and metrics used to assess environmental conditions require deeper attention. Most previous studies employed CO2 emissions as a measure of environmental degradation. Still, this metric seems insufficient because it deals only with air pollution. Other studies used the ecological footprint (EF) as an environmental indicator, encompassing numerous forms of pollution but overlooks biocapacity (Ngoc and Awan, 2022; Yang *et al.,*2023). In this case, recent studies recommended employing the load capacity factor (LCF), representing a broader environmental quality assessment (Siche *et al.,* 2010; Ni *et al.,* 2022). The previous discussion underscores the urgent need for a more in-depth investigation of the interdependence between oil rents, renewable energy, technological innovation, and environmental quality in Saudi Arabia.

This research aims to enhance the current body of literature dealing with the environmental conditions in Saudi Arabia by investigating the impacts of green technological innovation (GTI), clean energy, and oil rents on the load capacity factor between 1988 and 2021. Saudi Arabia is seriously concerned with climate change and environmental degradation (Ben-Salha and Zmami, 2023). Between 1990 and 2020, greenhouse gas (GHG) emissions increased from 239.7 metric tons of CO2 equivalent to 712.5 metric tons (Raggad *et al.,* 2024). According to Alkhathlan and Javid (2015), Saudi Arabia is among the eighth carbon-emitting economies worldwide. In light of this circumstance, Saudi Arabia aimed to reduce GHG emissions by 278 million tons of CO2eq by 2030. To this end, Saudi Arabia has implemented significant measures, including establishing the National Renewable Energy Program in 2017 and introducing the Saudi Green Initiative in 2021. To develop appropriate policy recommendations, it is crucial to have a comprehensive understanding of factors inducing environmental degradation. This research fits into this framework as it aims to empirically assess the repercussions of GTI, clean energy sources, and oil rents on environmental quality in Saudi Arabia.

This research distinguishes itself from previous studies on Saudi Arabia in several ways. First, this paper considers the LCF as an indicator of environmental conditions. Indeed, prior research used CO2 emissions to measure environmental deterioration. Although this proxy seems adequate to quantify environmental degradation in a given country, it only considers air pollution. It fails to account for other forms of pollution, including water, forest, and soil. This could explain why the latest studies have utilized EF to assess environmental conditions (Ragmoun, 2023a,b; Touati and Ben-Salha, 2024). However, the EF does not account for the supply of natural capital. To overcome this drawback, Siche *et al.* (2010) suggested LCF as the most adequate indicator of environmental quality. This indicator quantifies how a country can sustain its population regarding the available lifestyle (Fang *et al.,* 2024). Calculated as the ratio between biocapacity and the EF, it takes a value of one or more when the biocapacity is equal to or higher than the EF, indicating a sustainable ecosystem. It indicates an unsustainable ecosystem if the biocapacity is lower than the EF (Pata *et al.,* 2024). Therefore, the LCF outperforms standard environmental measures, such as CO2 emissions, since it simultaneously accounts for biocapacity and EF. The LCF has gained growing popularity in recent empirical research as it has been considered in many studies (Alharbey and Ben-Salha, 2024; Pata *et al.,* 2024; Djedaiet *et al.,* 2024). However, most works dealing with Saudi Arabia employed GHG emissions or the EF as indicators of environmental quality. Only recent research by Adebayo *et al.* (2024) explored the implications of some factors, including institutional quality, on the LCF in Saudi Arabia. Second, this paper is the pioneer in examining the combined effects of GTI, clean energy, and oil rents on environmental sustainability in Saudi Arabia. Although some recent studies have focused on the environmental consequences of many factors in Saudi Arabia, a lack of knowledge on the environmental effects of eco-innovation in Saudi Arabia still exists. Additionally, it remains crucial to investigate the environmental repercussions of renewable energy in Saudi Arabia. Although Saudi Arabia is an oil-exporting country, several measures have been undertaken to reduce the demand for fossil fuels, mainly oil and gas, and boost investments in clean energy sources. It is therefore important to check whether there has been any improvement in environmental indicators after increasing the use of clean energy. Moreover, this research also evaluates the environmental effects of oil rents. This is mainly motivated by the ambiguity associated with the environmental implications of rents in resource-abundant countries like Saudi Arabia. By promoting energy transition, resource rents can reduce environmental deterioration. On the other hand, when used to fund the exploration and extraction of fossil fuels, they can contribute to environmental deterioration (Touati and Ben-Salha, 2024). Third, this empirical investigation uses quantile regression to assess the implications of GTI, clean energy, and oil rents on the LCF in Saudi Arabia. Unlike conventional OLS-based techniques, quantile regression enables accounting for the dependent variable distribution and generates more accurate findings. By doing so, our research may define valuable insights and appropriate policy recommendations.

The remainder of this research paper is organized as follows. The second section examines the current literature, and the third section details the model, research methods, and data. The fourth section discusses the findings. Finally, the fifth section closes the research by outlining empirical findings and policy recommendations.

2. Brief literature review

2.1 GTI and environmental sustainability

GTI entails developing new technologies that enhance efficiency, cost-effectiveness, and the transition to clean energy. In addition, GTI is recognized as a performant instrument to mitigate CO2 emissions, enhance energy efficiency, and foster economic development. Xin *et al.* (2022) indicated that GTI can effectively mitigate CO2 emissions by enabling the development of eco-friendly processes or products that improve energy efficiency. Indeed, organizations allocating resources toward research and development and innovation initiatives to further develop clean energy technologies may yield favorable environmental outcomes by reducing GHG emissions. Previous studies provided compelling evidence highlighting the beneficial effects of GTI on the environment. Apergis *et al.* (2023) investigated the impacts of energy technology investments and GTI on the EF and LCF in the United States. The authors concluded that investments in GTI had no significant effect on environmental sustainability. On the contrary, Aydin and Degirmenci (2023) concluded that green innovation and technological diffusion are favorable and mandatory for promoting sustainable environmental practices in the European Union. Avcı *et al.* (2024) also analyzed the interdependence between tourism, GTI, and environmental conditions in most visited countries. This research indicates that GTI improves long-term environmental quality. Furthermore, Javed *et al.* (2024) explored the implications of green innovation on LCF in 10 manufacturing countries between 1990 and 2019 using the CS-ARDL model. The outcomes suggest that green innovation improves environmental quality in both the short- and long-run. Ali *et al.* (2023) examined the implications of technological innovation on Saudi carbon emission intensity. The quantile-based regression suggested that technological innovation reduces carbon emission intensity. Finally, Islam (2024) analyzed the implications of GTI on CO2 emissions using the nonlinear ARDL model. The results indicate that the low GTI level fails to mitigate environmental pollution in Saudi Arabia and remains insignificant in the short and long term.

2.2 Clean energy and environmental sustainability

The interconnection between renewable energy and environmental conditions has gained significant academic attention. Renewable energy sources are considered emission-free and sustainable alternatives that are determinant to protecting and preserving the environment (Rehman *et al.,* 2023). According to Saidi and Mbarek (2016), clean energy helps to limit CO2 emissions while stimulating sustainable development and resolving environmental issues. Previous studies suggested that clean energy may reduce emissions at the national level (Dong *et al.,* 2018), regional level (Waheed *et al.,* 2018), and worldwide (Ben-Ahmed and Ben-Salha, 2024). Contrary to these studies, others consider the environmental impact of renewable energy as limited or insignificant (Khoshnevis and Shakouri, 2018; Alola *et al.,* 2022). Regarding Saudi Arabia, AlNemer *et al.,* (2023) concluded that renewable energy reduces carbon emissions in the short term. Furthermore, Toumi and Toumi (2019) employed the nonlinear ARDL model to analyze the asymmetric effects of renewable energy on CO2 emissions in Saudi Arabia. The authors concluded that positive and negative variations in renewable energy consumption reduce long-term emissions. Finally, Kahia *et al.* (2021) studied the linkages between renewable energy, economic growth, and environmental conditions in Saudi Arabia to extend this idea. The simultaneous equation results confirm a bidirectional connection between CO2 emissions and renewable energy. Finally, the positive impact of green energy on CO2 emissions in Saudi Arabia was also revealed by Kahia *et al.* (2023).

2.3 Oil rents and environmental sustainability

According to Sweidan and Elbargathi (2022) and Touati and Ben-Salha (2024), the impact of oil rents on the environment may be positive or negative. Indeed, natural resource rents, including oil, may improve environmental quality when the corresponding revenues are allocated towards developing the renewable energy sector and promoting energy transition. On the contrary, resource rents may contribute to environmental degradation when utilized to expand the exploration and extraction of fossil fuels (Touati and Ben-Salha, 2024). Therefore, the environmental effects of resources are ambiguous and remain an empirical issue. For example, Damrah *et al.* (2022) concluded that natural resources increase EF in selected oil-exporting economies. In the same line of idea, Ulucak and Baloch (2023) confirmed a significant positive effect of natural resource rent on CO2 emissions in the US. In addition, Zambrano-Monserrate *et al.* (2023) revealed that not all natural resources have the same degree of environmental impact. Mahmood and Saqib (2022) estimated the asymmetric effects of economic growth and oil rents on CO2 emissions between 1970–2019 in the selected OPEC countries. In addition, Ben-Salha and Zmami (2023) conducted a disaggregated analysis of the natural resource rents-EF linkage in Saudi Arabia. They suggested a positive association between oil rents and EF in the long run. Finally, Touati and Ben-Salha (2024) concluded that natural resources cause damage to the environment in GCC nations and that oil has the most detrimental impact.

3. Model, data and methods

3.1 The augmented STIRPAT model

Dietz and Rosa (1994) presented the STIRPAT model, an extension of Ehrlich and Holdren's IPAT model from 1971. The objective of the model is to identify the socioeconomic factors, notably population (P), affluence (A), and technology (T), that affect environmental degradation (I). The STIRPAT model can be expressed in the following manner:

$$I_t = \varphi P_t^{\alpha} A_t^{\beta} T_t^{\gamma} \varepsilon_t \quad (1)$$

Equation (1) may be written after applying the logarithmic transformation as follows:

$$logI_t = \varphi + \alpha logP_t + \beta logA_t + \gamma logT_t + \varepsilon_t \quad (2)$$

I, P, A, and *T* are represented by LCF, population, GDP per capita, and energy intensity, respectively. Coefficients $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ and $\boldsymbol{\gamma}$ are to be estimated, with $\boldsymbol{\varphi}$ representing the constant term and $\boldsymbol{\varepsilon_t}$ denoting the error term.

Finally, Equation (2) is augmented by three variables to obtain the final equation to be estimated, which may be written as follows:

$$logLCF_t = \varphi + \alpha logPOP_t + \beta logGDP_t + \gamma logEI_t + \theta logOILR_t + \lambda logGTI_t + \phi logREN_t + \varepsilon_t \quad (3)$$

Table 1
Definitions and sources of the variables

Acronym	Variable	Definition	Unit	Source
LCF	Load capacity factor	Biocapacity to ecological footprint	Index	GFN
OILR	Oil rents	Oil rents as a share of GDP	%	WDI
GTI	Patents in environment-related technologies	Number of environment-related inventions as a share of domestic inventions in all technologies	%	OECD
REC	Renewable energy consumption	Consumption of all renewable energy sources	TWh	EI
POP	Population	Total population size	Person	WDI
EI	Energy intensity	Energy consumption per GDP	Kilowatt-hours per dollar	EIA
GDP	GDP per capita	Real gross domestic product to population	Constant 2015 US dollar	WDI

EI: Energy Institute; EIA: U.S. Energy Information Administration; GFN: Global Footprint Network. OECD: Organisation for Economic Co-operation and Development; WDI: World Development Indicators.

3.2 Data

The research investigates the impacts of green technological innovation (GTI), renewable energy consumption (REC), and oil rents (OILR) on environmental conditions in Saudi Arabia between 1988 and 2021. Environmental sustainability is measured via the load capacity factor (LCF) obtained from the Global Footprint Network. The Energy Institute provides data on REC, while the GTI, measured by the number of environment-related inventions as a ratio to domestic inventions, comes from the OECD. Oil rents are measured by oil revenues as a share of GDP. In addition to the variables indicated above, the model incorporates three control variables: total population, real GDP per capita, and energy intensity, which is defined as energy consumption per unit GDP. Table 1 includes a description of the variables and their sources.

3.3 Methodology

Before implementing the quantile regression, a series of tests, summarized in Figure 1, are conducted:

- Normality analysis: It is important to check whether the dependent variable (LCF) is normally distributed. In the presence of a nonnormally distributed dependent variable, quantile regression is appropriate.
- Unit root analysis: It is also important to check the order of integration of all variables, as the OLS-based techniques and quantile regression should be applied for stationary variables.
- Cointegration analysis: The aim is to check whether a long-run relationship exists between the variables under consideration.
- OLS-based techniques: The OLS, fully modified OLS (FMOLS), and dynamic OLS (DOLS) are performed as benchmark models that do not consider normality issues.
- Quantile regression: Quantile regression is applied to assess how the dependent variable responds to the various explanatory variables across different distribution orders of the dependent variable. The quantile regression was first developed by Koenker and Bassett (1978). A conditional quantile of y_t given x_t may be expressed in the following general form:
- $$Q_{y_i}(\omega|x_i) = x_i^T \phi_\tau \quad (4)$$
- where $Q_{y_i}(\omega|x_i)$ stands for the γ^{th} conditional quantile of y_i. y_i is the dependent variable. In contrast, x_i is the independent variable. ϕ_τ represents the different coefficients to be estimated for the different conditional τ^{th} quantiles of the dependent variable y_i. Finally, ω represents the different quantile orders and ranges between 0 and 100. This study considers 10 quantile orders (10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th, and 90th).
- Causality analysis: Finally, the study conducts a causality analysis using the Toda-Yamamoto (TY) causality test proposed by Toda and Yamamoto (1995).

4. Empirical findings

4.1 Normality analysis

It is important to conduct a normality analysis before applying quantile regression, as this latter is suitable for a nonnormally distributed dependent variable. The normality test results are reported in Table 2. As shown, the Skewness/Kurtosis joint test rejects normality at the 10% level, while the Shapiro-Wilk W and Shapiro-Francia W tests reject normality at 1%. The normality tests suggest that the dependent variable (LCF) is not normally distributed, justifying quantile regression.

4.2 Stationarity analysis

This study performs the Bootstrap ADF unit root test and Kapetanios (2005) unit root test with structural breaks. The first test has various advantages compared to the standard ADF unit root test, including higher power in detecting unit roots. However, it has low power when the data has structural breaks. The Kapetanios (2005) unit root test with multiple structural breaks is implemented to account for this issue. The findings are reported in Table 3. Both tests show that series are not stationary at levels. When considering variables at first differences, the null hypothesis of a unit root is rejected. Therefore, all series are stationary at first difference. Another interesting result from the table is that the various series have different breakpoint dates. For example, LCF had breakpoints in 1994 and 1999, whereas breakpoints for renewable energy consumption occurred in 2010 and 2015. This may be related to the fact that the policymakers in Saudi Arabia have recently

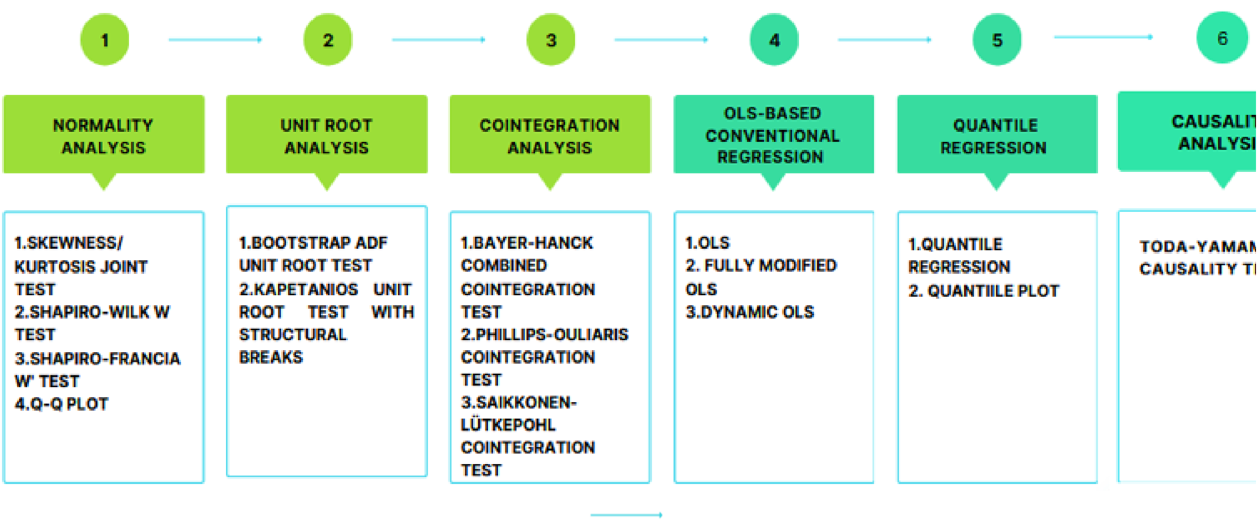

Fig. 1 Empirical methodology

Table 2
Normality analysis

Test	statistic	p-value
Skewness/Kurtosis joint test	4.790*	0.091
Shapiro-Wilk W test	0.876***	0.001
Shapiro-Francia W' test	0.889***	0.003

*** and * denote the rejection of the null hypothesis at 1 and 10%, respectively

Table 3
Unit root test results

Variables	Bootstrap ADF unit root test		Kapetanios (2005) unit root test	
	t-statistic	p-value	t-statistic	TB1/TB2
Levels				
$lnLCF$	-1.252	0.431	-5.454	1994/1999
$lnOILR$	-2.386	0.220	-2.899	2008/2014
$lnGTI$	-2.693	0.103	-4.047	1992/2003
$lnREC$	-1.127	0.666	-4.482	2010/2015
$lnPOP$	-1.908	0.126	-3.488	2004/2016
$lnEI$	-1.289	0.858	-5.039	2009/2015
$lnGDP$	-1.777	0.395	-5.225	2002/2009
First-differences				
$\Delta lnLCF$	-6.804***	0.000	-9.389***	1994/1999
$\Delta lnOILR$	-6.764***	0.000	-7.225***	2008/2014
$\Delta lnGTI$	-10.961***	0.000	-6.477**	1997/2004
$\Delta lnREC$	1.797*	0.075	-17.474***	2011/2016
$\Delta lnPOP$	-2.473***	0.000	-7.323***	2004/2016
$\Delta lnEI$	-6.029***	0.000	-6.318**	1999/2015
$\Delta lnGDP$	-4.939***	0.000	-7.183***	2002/2010

***, **, and * denote the rejection of the null hypothesis at the 1, 5, and 10% levels, respectively. For the Kapetanios (2005) unit root test, TB1 and TB2 represent the dates of the breakpoints.

adopted significant measures to foster energy transition and increase the share of renewable energy in the energy mix.

4.3 Cointegration analysis

To check whether there are long-term relationships between the series, this study implements three cointegration tests: Bayer-Hanck combined cointegration test (B-H) test, Phillips-Ouliaris cointegration test (P-O) and Saikkonen-Lütkepohl cointegration test (S-L). Table 4 summarizes the results. Both versions of the B-H test suggest rejecting the null hypothesis at the 1% level and, therefore, the presence of significant long-run linkages. These findings are further confirmed using the P-O cointegration test based on tau and z statistics. In line with previous findings, the S-L cointegration test indicates the presence of cointegration at the 1% level. Consequently, the different cointegration tests strongly confirm the existence of significant long-run linkages. This indicates that the explanatory variables have long-run linkages with environmental conditions in Saudi Arabia. At this stage, estimating how these variables affect environmental quality is essential.

4.4 OLS-based conventional regression results

Although the preliminary analysis suggested the nonnormal distribution of the dependent variable and the suitability of the quantile regression for the analysis, three OLS-based

Table 4
Cointegration test results

Bayer-Hanck combined cointegration test			
Test	Statistic		Decision
EG-JOH	56.854***		cointegration
EG-JOH-BO-BDM	113.306***		
Phillips-Ouliaris cointegration test			
Test	Statistic	p-value	Decision
Phillips-Ouliaris tau-statistic	-5.278*	0.089	cointegration
Phillips-Ouliaris z-statistic	-31.429*	0.052	
Saikkonen-Lütkepohl cointegration test			
H0	Statistic	p-value	Decision
0	129.10***	0.010	cointegration
1	111.07***	0.000	
2	52.39	0.416	
3	29.90	0.652	
4	10.25	0.972	
5	6.89	0.676	
6	2.2	0.475	

*** and * denote the rejection of the null hypothesis at the 1 and 10% levels, respectively.

Table 5
Results of OLS-based techniques

Variables	Standard OLS		Fully Modified OLS		Dynamic OLS	
	Coef.	p-value	Coef.	p-value	Coef.	p-value
lnOILR	-0.046	0.121	-0.054**	0.036	-0.022	0.627
lnGTI	0.027*	0.087	0.028**	0.035	-0.097***	0.002
lnREC	0.091*	0.091	0.102**	0.031	1.534***	0.007
lnPOP	-0.563***	0.000	-0.591***	0.000	-1.662***	0.000
lnEI	0.023	0.830	0.054	0.597	1.404***	0.000
lnGDP	0.175	0.213	0.183	0.124	1.177***	0.000
constant	8.148***	0.000	8.512***	0.000	14.637***	0.000

***, ** and * denote the statistical significance at 1, 5 and 10% level, respectively.

techniques, namely, standard OLS, FMOLS, and DOLS techniques, are implemented for comparison purposes. The findings are presented in Table 5.

Different conclusions are drawn from the analysis concerning the coefficients' sign, magnitude, and significance. While the coefficient associated with oil rents is negative using the three estimation techniques, it is only significant when using FMOLS. While lacking support from the OLS and DOLS, this finding suggests that oil rents reduce the LCF and deteriorate environmental quality in Saudi Arabia. These results align with some previous studies indicating that increased oil rents induce additional financial resources, promoting additional investment in the oil industry and deteriorating the environment (Tiba, 2021). The findings also indicate that GTI positively impacts LCF using the OLS and FMOLS. This suggests that GTI can increase LCF and enhance environmental indicators. On the contrary, DOLS shows a negative and significant impact. The existence of conflicting results indicates that the findings lack robustness, partly because OLS, DOLS and FMOLS disregard normality issues. Finally, using all techniques, the coefficient associated with REC is positive and statistically significant. Therefore, while renewable energy adoption in Saudi Arabia is still in its early stages, it has improved environmental quality. Indeed, policymakers in Saudi Arabia have prioritized increasing the proportion of renewable energy in total energy consumption during the last decades. One of the Saudi Vision 2030 objectives is to generate 50% of electricity from renewable sources by 2030. The table also indicates that the significance of coefficients associated with energy intensity and GDP per capita depends on the employed technique. The OLS and FMOLS indicate that both variables have no significant effects on LCF, while the DOLS suggests that both improve environmental quality. Once again, such a divergence supports the fact that the findings derived from these techniques are not robust. On the contrary, the impact of the population is negative and significant in all specifications. These findings underscore the adverse consequences of population on the environment.

Despite the previous analysis providing some insights into how LCF reacts to the different factors considered, it fails to consider the nonnormal distribution of LCF confirmed in Table 2. This could partly induce divergence and inconsistency of the results reported in Table 5. To address such a limitation, this study implements the quantile regression.

4.5 Quantile regression results

This section aims to enhance our comprehension of factors affecting LCF using quantile regression. Indeed, quantile regression allows for the analysis of the effects of each explanatory variable on LCF under various quantiles of LCF (low, medium, high). The present study selects the 10th, 20th, and 30th as the low quantiles, while the 40th, 50th, and 60th are medium quantiles. Finally, the high quantiles are the 70th, 80th and 90th. The quantile regression findings are reported in Table 6, while Figure 2 reports the coefficients across all quantiles.

The table shows that oil rents have negative coefficients for all quantiles. Nevertheless, the coefficients lack statistical significance for low quantiles (20th, 30th), though they become significant starting from the 40th quantile. Another interesting outcome from Table 6 is that the magnitude of coefficients

Table 6
Quantile regression results

Variables	Low quantiles			Medium quantiles			High quantiles		
	10th	20th	30th	40th	50th	60th	70th	80th	90th
lnOILR	-0.025*	-0.021	-0.011	-0.027**	-0.036*	-0.079***	-0.088***	-0.053***	-0.108***
	(0.099)	(0.259)	(0.456)	(0.024)	(0.086)	(0.001)	(0.000)	(0.008)	(0.000)
lnGTI	0.035***	0.028***	0.006	0.0009	0.007	0.017	0.017*	0.026**	0.047***
	(0.000)	(0.008)	(0.418)	(0.877)	(0.526)	(0.137)	(0.088)	(0.013)	(0.001)
lnREC	0.114***	0.100***	0.052*	0.006	0.044	0.054	0.060*	0.175***	0.253***
	(0.000)	(0.005)	(0.061)	(0.764)	(0.239)	(0.154)	(0.073)	(0.000)	(0.000)
lnPOP	-0.579***	-0.552***	-0.454***	-0.397***	-0.480***	-0.550***	-0.573***	-0.638***	-0.804***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
lnEI	0.079	0.054	-0.024	-0.117***	-0.014	-0.002	0.049	0.062	0.250**
	(0.152)	(0.427)	(0.664)	(0.010)	(0.850)	(0.971)	(0.468)	(0.374)	(0.012)
lnGDP	0.252***	0.240***	0.161**	0.200***	0.168*	0.216**	0.264***	0.113	-0.168
	(0.001)	(0.010)	(0.029)	(0.000)	(0.093)	(0.036)	(0.004)	(0.210)	(0.166)
constant	7.433***	7.142***	6.435***	5.331***	6.888***	7.723***	7.586***	10.006***	15.404***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

***, ** and * denote the statistical significance at 1, 5 and 10% level, respectively. Numbers under parentheses are p-values.

associated with oil rents (in absolute value) generally increases when moving from medium to high quantiles. The most detrimental impact of oil rents on environmental quality (-0.108) is observed for the highest quantile (90th). These outcomes suggest that oil rents do not affect LCF and environmental quality for low quantiles, i.e., when LCF is low. However, when LCF grows, i.e., there is an improvement in environmental quality, oil rents start deteriorating environmental quality. For instance, a 1% rise in oil rents induces a degradation of the environmental quality by 0.036% when environmental quality is moderate and 0.108% when environmental quality is in the best situation. This finding can be explained by the fact that improving environmental conditions may result in more oil exploration and exploitation activities to increase government revenues. Such a situation may induce more environmental degradation under good environmental conditions. This finding represents one of the contributions of this study, as the quantile regression allows analyzing the environmental effects of oil rents under different environmental conditions. The previous literature, including Mahmood and Saqib (2022), concluded that oil rents have detrimental effects on the environment in Saudi Arabia. Nevertheless, it fails to identify when the adverse environmental impacts of oil rents occur. Ben-Salha and Zmami (2023 also concluded that oil rents increased EF and deteriorated the environment in Saudi Arabia. However, the analysis is based on the dynamic ARDL simulation approach, which does not account for normality.

Furthermore, Table 6 indicates that patents on environmental technologies have positive and statistically significant coefficients for low and high quantiles. This means that improving GTI improves LCF in Saudi Arabia. These outcomes are expected since green innovation allows for reducing the use of obsolete production methods and the dissemination of cutting-edge eco-friendly technologies. Furthermore, green innovation has the potential to lessen the use of fossil fuels, accelerate the shift towards renewable energy, and promote energy transition. The quantile regression shows that GTI has no significant coefficients for medium quantiles, suggesting that it has no impact on LCF during moderate/normal environmental quality. This implies that green innovation improves environmental quality only during poor and good environmental conditions. One potential explanation for these results is that when environmental conditions are poor, GTI may be implemented to improve environmental conditions. Indeed, during high pollution and environmental degradation periods, policymakers may formulate and implement various policies, including promoting green innovation. This could subsequently yield a favorable effect on environmental conditions. In addition, policymakers may be interested in further improving environmental conditions by encouraging green innovation when they are already good. These results represent one of the novelties of the current study since the previous literature, including Xin *et al.* (2022), revealed the important role of GTI in improving environmental conditions. On the contrary, Islam (2024) confirms that the low level of GTI patents in Saudi Arabia limits its effect on environmental pollution and is still insignificant in the short- and long-run. Our study outperforms the abovementioned studies, revealing that green innovation improves environmental quality only under poor and good environmental conditions. At the same time, no significant effects are identified under moderate/normal environmental conditions.

Regarding the outcomes of renewable energy on LCF, the table reveals that using clean energy benefits the environment, as the coefficients are positive and significant, mainly for low and high quantile orders. These outcomes are expected because adopting clean energy sources reduces the utilization of fossil fuels while simultaneously cutting GHG emissions. Furthermore, the beneficial impacts of renewable energy use on environmental quality could be linked to the efforts to foster green technological innovation, which reduces fossil fuel dependence and promotes energy transition in Saudi Arabia. These findings align with those in Table 5 and support many

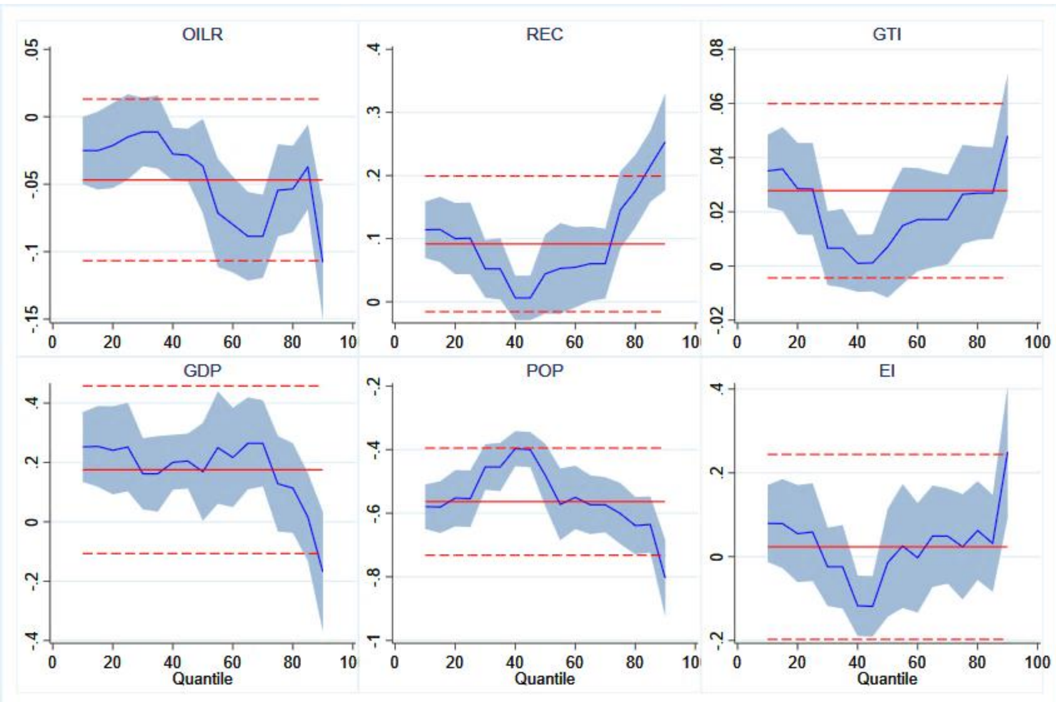

Fig. 2 Coefficients of the different explanatory variables using the quantile regression (blue line) and OLS (red line)

Table 7
Toda-Yamamoto causality test results

Null hypothesis	Chi-sq	p-value
lnOILR does not cause *lnLCF*	17.897***	0.000
lnGTI does not cause *lnLCF*	4.145	0.125
lnREC does not cause *lnLCF*	5.929*	0.051
lnPOP does not cause *lnLCF*	1.051	0.591
lnEI does not cause *lnLCF*	6.184**	0.045
lnGDP does not cause *lnLCF*	17.916***	0.000

***, ** and * denote the rejection of the null hypothesis at 1.5, and 10%, respectively.

previous studies on the repercussions of renewable energy on environmental quality in Saudi Arabia. For instance, Toumi and Toumi (2019) employed the nonlinear ARDL model and revealed that both positive and negative changes in renewable energy consumption reduce long-term CO2 emissions and protect the environment. Moreover, AlNemer *et al.* (2023) implemented the wavelet coherence analysis, revealing a positive connection between the two variables.

Concerning the control variables, findings reveal some heterogeneity regarding the sign and magnitude of coefficients. Indeed, the coefficients associated with GDP per capita are almost positive and significant for all quantiles except for the highest quantiles (80th, 90th). This means that GDP per capita increases LCF and improves environmental quality in Saudi Arabia. A 1% increase in GDP per capita induces a rise in LCF by 0.168% on average. This confirms that the Saudi economy has reached a stage where improved environmental conditions accompany increased production of goods and services. This could be linked to implementing innovative, environmentally friendly manufacturing techniques and using clean energy. On the contrary, the coefficients associated with the total population are negative and statistically significant for all quantiles. Indeed, an increase in population is frequently linked to a corresponding rise in urbanization, leading to a surge in energy consumption, heightened air and water pollution, rapid depletion of resources, and ultimately an increase in household waste. As mentioned previously, the population size in Saudi Arabia has more than doubled since 1990. In addition, the urban population has also expanded from 31% in 1960 to 85% in 2023 (World Bank, 2024). Finally, there is little evidence on the environmental implications of energy intensity, since coefficients are not statistically significant for most quantiles. Indeed, the coefficients are significant only for the 40th and 90th quantiles but with different signs. Therefore, it can be inferred that energy intensity does not have a robust environmental impact in Saudi Arabia across all environmental conditions. The evolution of coefficients associated with all variables across the different quantiles is plotted in Figure 2.

In summary, this study suggests that to address environmental degradation and foster the achievement of SDG13 in Saudi Arabia, reliance on fossil fuel energy should be reduced, and a prompt shift to renewable energy sources should be promoted, alongside the promotion of green technological innovation. Furthermore, climate action may need the allocation of oil revenues towards developing the renewable energy sector and implementing renewable energy projects, primarily solar installations.

4.6 Causality analysis

In the final stage of the empirical investigation, a causality analysis is carried out by employing the Toda-Yamamoto causality test initially proposed by Toda and Yamamoto (1995). According to Ben-Salha *et al.* (2023), the TY causality test outperforms conventional causality tests by handling data with different orders of integration and cointegration properties. The findings are reported in Table 7, while Figure 3 summarizes the causal relationship associations.

The results reject the null hypothesis of no Granger causality at the 1% significance level from oil rents to LCF and GDP per capita to LCF. This means that both variables strongly cause LCF, i.e., past values of oil rents and GDP per capita predict actual values of LCF in Saudi Arabia. Additionally, the table indicates that renewable energy consumption Granger causes LCF at the 10% level, while energy intensity has causality with LCF at 5%. These outcomes confirm that renewable energy

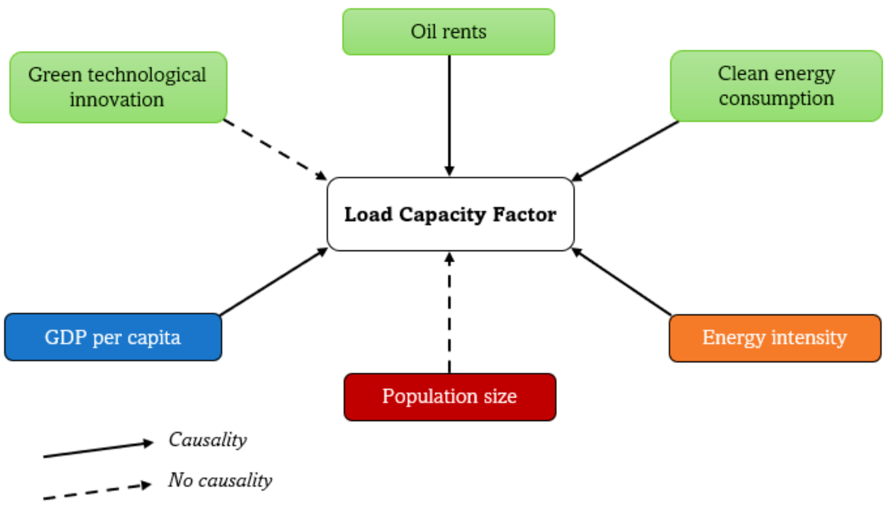

Fig. 3. Causal relationship associations

consumption and energy intensity allow the prediction of LCF in Saudi Arabia. Finally, there is no evidence of causality between GTI and population and LCF, thereby, there is no predictive power these two variables have on environmental quality.

5. Conclusion and policy recommendations

This research aims to assess the role of resource abundance, innovation, and clean energy on environmental conditions with the Saudi context. The preliminary data analysis suggested the nonnormal distribution of LCF, which confirms the necessity of implementing quantile regression. Furthermore, the stationarity analysis revealed that all series are I(1), while cointegration tests supported the existence of long-run links between LCF and the explanatory variables. Then, the OLS, fully modified OLS, and dynamic OLS techniques showed divergent/conflicting findings regarding the impacts of GTI, green energy, and oil rents on the LCF. Finally, the quantile regression provided some fresh evidence. Indeed, oil rents deteriorate environmental quality, particularly under moderate and good environmental conditions, with a high adverse impact during good conditions. On the contrary, renewable energy consumption and green innovation improve LCF, mainly under poor and good environmental conditions. The quantile regression also suggests that GDP per capita positively affects environmental quality, while the population is identified as a substantial source of ecological deterioration. Finally, no significant implications of energy intensity on environmental conditions are identified using the quantile regression. The Toda-Yamamoto causality test indicates significant causal relationships between oil rents, GDP per capita, renewable energy consumption, and energy intensity to environmental quality.

Based on these findings, some policy recommendations to improve environmental quality and achieve SDG13 in Saudi Arabia may be provided. First, oil rents are considered a source of environmental deterioration. Hence, it is important to implement effective natural resources management to protect the environment. This can be achieved by leveraging oil revenues to enhance investments in renewable energy projects and foster the expansion of the renewable energy industry. Furthermore, enforcing rigorous regulations to reduce pollution caused by oil extraction and processing activities may improve environmental quality. In addition, adopting green technology innovation and utilizing renewable energy sources have been proven to improve the environment. Therefore, developing sustainable technologies and practices to safeguard the environment is important for Saudi Arabia. This may be achieved by designing policies to attract international corporations involved in environmentally sustainable technologies and providing financial incentives and tax reductions. The encouragement of domestic firms to substitute outdated technologies with green technologies might also reduce pollution. Moreover, promoting green hydrogen projects may represent an opportunity for Saudi Arabia to accelerate the energy transition process. Finally, population size is found to deteriorate the environment. Consequently, it is essential to foster awareness about environmental concerns through public campaigns and educational programs.

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