

Climate change and sustainable development new evidence from the Gulf cooperation Council economies

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ABSTRACT

This study explores the effects of climate change, trade, population, foreign direct investment, GDP, technological innovation, and natural resource rents on sustainable development in Gulf Cooperation Council (GCC) economies from 2001 to 2020. The primary objective is to understand how these factors contribute to or hinder sustainable development in the region. Using the descriptive statistics, correlation analysis, unit root tests, cointegration tests, and, Quantile Autoregressive Distributed Lag model, Quantile on Quantile, Granger causality tests, we assess the short- and long-term relationships between these variables. The findings indicate that technological innovation and climate change significantly influence sustainable development, especially at the lower and mean quantiles, suggesting that adapting to technological change and mitigating climate change are key to sustainability. Additionally, the study reveals complex, nonlinear relationships among these variables, with technological innovation, GDP, and population exerting long-term impacts, whereas natural resource rents and FDI negatively affect sustainability in the short term. The Granger causality results further show that variables such as temperature, natural resources, and FDI influence sustainable development, while GDP, population, and technological innovation exhibit bidirectional causal relationships. These results have important policy implications for enhancing sustainability in the GCC region by integrating climate adaptation strategies and fostering technological advancement.

1. Introduction

Climate change presents a significant challenge for economies globally, particularly for Gulf Cooperation Council (GCC) countries. Comprising Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, the GCC region is highly dependent on oil and gas exports, which account for a substantial portion of their GDP. This economic dependence, while fueling growth and development, also exposes the region to severe environmental risks associated with global warming, water scarcity, and desertification (Ganda, 2022a). The region's vulnerability to climate change is particularly concerning given the escalating global demand for energy, environmental consequences of fossil fuel extraction, and increasing frequency of extreme weather events (Usman et al., 2021). In this context, sustainable development that balances economic growth with environmental stewardship is essential for the future prosperity of these nations (Raman et al., 2024). However, GCC countries face unique challenges in addressing climate change because of their reliance on non-renewable resources and the need to diversify their economies into more sustainable sectors (Majeed

et al., 2021).

This study seeks to address a significant gap in empirical studies by exploring the effects of climate change, trade, technological advancements, foreign direct investment (FDI), and natural resource rents on sustainable development in GCC countries. While most existing studies have concentrated on either developed nations or global trends, there is a lack of research specifically analyzing these factors within the GCC context (Bekhet et al., 2017). Given a region's unique economic and environmental characteristics, it is essential to understand how climate change dynamics interact with the region's economic activities to affect sustainable development outcomes (Dam et al., 2024).

The choice to focus on the GCC region is driven by its distinctive economic structure, which relies heavily on the extraction and export of fossil fuels. As the global economy moves towards cleaner, renewable energy sources, the GCC faces considerable challenges in transitioning from an oil-dependent to a more diversified and sustainable economy (Javaid et al., 2022). Besides its dependence on oil and gas, GCC countries are particularly susceptible to climate-related risks, such as increasing temperatures, droughts, and water shortages, which pose

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significant threats to both economic stability and public welfare (Gyamfi et al., 2022). These vulnerabilities make the GCC an ideal region for studying how the interaction between climate change, technological innovation, and economic growth can impact long-term sustainable development (Gyamfi et al., 2022).

This study highlights the increasing significance of the United Nations' Sustainable Development Goals (SDGs), especially SDG 13 (Climate Action), SDG 7 (Affordable and Clean Energy), and SDG 12 (Responsible Consumption and Production). These international objectives aim to address climate change, improve energy efficiency, and encourage sustainable economic practices, which are particularly pertinent to the GCC region (Al-Maadid et al., 2025a, 2025b; Raman et al., 2024). Nonetheless, empirical research has been conducted on the specific connections between climate change and sustainable development within the GCC (Bekhet et al., 2017). Although some studies have examined the effects of economic growth, FDI, and technological innovation on sustainability in other areas, comprehensive research on how these elements interact in the GCC context is lacking (Raman et al., 2024).

This study seeks to fill this gap by offering an in-depth analysis of the impacts of climate change, trade, urbanization, FDI, and technological innovation on sustainable development in this vital region. The contributions of this study are noteworthy in several respects. First, it presents a new empirical analysis using sophisticated econometric methods, such as the Quantile Autoregressive Distributed Lag (QARDL) model, unit root tests, correlation analysis, Granger causality tests, and cointegration tests, to investigate the short- and long-term relationships between climate change and sustainable development across quantiles (Ganda, 2022b; Usman et al., 2021). Unlike earlier studies that often concentrated on aggregate, linear relationships, this approach provides a more detailed understanding of how these factors affect sustainable development at various distribution points, capturing both extreme and average effects (Razzaq and Yang, 2023). This method offers insight into the varied impacts of climate change and other factors across the GCC region, providing a more comprehensive perspective on the dynamics involved.

Second, this study considers a wide range of variables that have not been extensively studied together within the GCC context. Beyond climate change, it investigates the impact of technological innovation, trade openness, FDI, and natural resource rents on sustainable development (Javaid et al., 2022). Although earlier studies have looked at these factors separately, this study provides a more comprehensive view by examining their combined effects on sustainability outcomes. The significance of technological innovation is particularly highlighted, as progress in green technologies and renewable energy is vital for minimizing the environmental footprint of economic activities, especially in economies reliant on fossil fuels, such as the GCC (Dam et al., 2024).

The conclusions of this study have significant policy implications. Policymakers in the GCC region can use these findings to identify crucial areas in which interventions are necessary to promote sustainable development. For instance, research might emphasize the importance of increased investment in renewable energy technologies, which could not only reduce greenhouse gas emissions but also encourage economic diversification (Ganda, 2022b). Additionally, examining the link between FDI and sustainability could offer valuable insights into directing foreign investment in green technologies and sustainable industries (Raman et al., 2024). By providing empirical evidence on the intricate connections between climate change, economic activities, and sustainable development, this study provides guidance on how the GCC can meet its sustainability objectives, while addressing the challenges of a rapidly evolving global economy.

Beyond its theoretical contributions, this study is both timely and highly pertinent. As GCC nations encounter increasing demands to tackle climate change and shift towards more sustainable economic frameworks, it is crucial to comprehend the elements that affect sustainable development in this area (Gyamfi et al., 2022). By

concentrating on the unique challenges and opportunities within the GCC, this study offers valuable insights that can inform regional and global initiatives aimed at fostering sustainability in the face of climate change. Additionally, the study's outcomes enrich the broader discourse on sustainable development, providing fresh perspectives on the significance of technological innovation, FDI, and natural resource management in achieving enduring sustainability (Razzaq and Yang, 2023). In summary, this study significantly enhances the empirical literature by exploring the connections between climate change and sustainable development within GCC economies. This study's originality is evident in its thorough examination of various factors, its application of advanced econometric techniques, and its focus on a region that has been largely overlooked in sustainability research. The findings of this study are crucial for policymakers, researchers, and other stakeholders dedicated to advancing sustainable development in the context of climate change, particularly in regions such as the GCC, where the challenges and opportunities for sustainability are distinct (Dam et al., 2024).

The remainder of the study is organized as follows. Section 2 identifies prior research related to the issue under consideration. Section 3 discusses the techniques adopted in this study and describes the data. Section 4 presents the empirical results, including the prediagnostic test, QARDL model, quantile-on-quantile model, and Granger causality test for robustness. Finally, the study's shortcomings, policy implications, and conclusions are presented in the last section.

2. Literature review and theoretical framework

2.1. Theoretical studies and empirical research

The GCC region is characterized by an arid climate and significant economic reliance on fossil fuels. Therefore, it is facing unique challenges in the context of global climate change. Recent studies (Benlemlih and Yavaş, 2024; Mayembe et al., 2023) have focused on the implications of rising air temperatures on the environment and sustainable development around the Arabian Gulf. The extreme climatic conditions of the region, exacerbated by global warming, pose critical threats to public health, water resources, and biodiversity (Ojja and Nicholaus, 2023). Additionally, the socioeconomic framework of GCC countries, which depends heavily on energy-intensive industries and water desalination, underscores the urgent need for comprehensive adaptation and mitigation strategies. The concept of sustainable development is ambiguous in the literature and may depend on global leaders' perceptions and promotion. Climate change, technological innovation, natural resource rents, trade flexibility, sustainable energy, FDI, and urban growth influence sustainable development (Ullah et al., 2021; Wang et al., 2023).

Recent studies have highlighted a crucial link between natural resources and CO₂ emissions. Natural resources play a crucial role in the provision of raw materials, income, employment, and ecosystem services. According to recent studies, a significant relationship exists between natural resources and carbon dioxide emissions. Moreover, there are often concerns regarding the environmental effects of harnessing natural resources (He et al., 2024). Li et al. (2023) analyzed the link between China's natural resources and environmental regulation and revealed that lowering resource availability and increasing regulations can lower CO₂ emissions. Khan and Hassan (2024) revealed that natural resource rents significantly increase CO₂ emissions in 141 developing economies, highlighting the environmental challenge of reliance on natural resources for sustainable development. Dagar et al. (2022) suggested that renting natural resources along with using clean energy might effectively halt environmental degradation. Altinoz and Dogan (2021) examined the relationship between natural resource rents and CO₂ emissions, and reported a negative correlation. Nathaniel et al. (2021) discovered that natural resource rents significantly contributed to the rise in CO₂ emissions in Latin American and Caribbean countries.

In contrast, Lorente et al. (2023), Alvarado et al. (2021), and Caiado et al. (2018) found that the use of earth's resources and green technology to minimize pollutants in our natural surroundings promotes sustainable development.

Previous findings on the connection between technological advancement and sustained development are mixed because technological innovation has both beneficial and detrimental effects on sustainable development. For example, Kunz (2016) and Javaid et al. (2022) focused on innovations for the next generation of industries, such as the IoT, AI, and ML, which can increase efficiency, reduce waste, and advance sustainable practices in water-related resource management and mining industries. In addition, blockchain-based systems can improve traceability and transparency. From a different perspective, Arranz et al. (2021) showed that technological innovation significantly controls the release of carbon dioxide emissions in BRICS economies. Similarly, Y. Sun et al. (2008) reported that technological advancement helped reduce carbon emissions in the eastern region of China from 1985 to 2005. In their studies of 28 OECD countries from 1990–2014, Mensah et al. (2018) and Alvarez-Herranz et al. (2017) observed that green technological implementation reduced harmful gases and improved environmental quality by mitigating environmental degradation. Similarly, Jiakui et al. (2023) and Razzaq and Yang (2023) highlight the beneficial effects of green technological advancement on China's green growth and sustainable development.

Similarly, Kumar and Managi (2010) argued that advancements in technology decrease pollution in developed countries and increase pollution in most developing markets. Mehmood et al., 2024 examined greenhouse gas emissions in Pakistan from 1975 to 2020. They concluded that eco-friendly techniques reduce pollutants, but more technological advancements and R&D help mitigate environmental degradation. They highlighted the importance of green inventions for achieving sustainable long-term goals and concluded that technological innovation has a positive relationship with sustainable development.

FDI is a global solution for economic development, but it also incurs societal, economic, and environmental costs. The connection between FDI, economic growth, and the environment is expressed as the environmental Kuznets curve, which has been widely debated in the literature (Ayamba et al., 2020). The EKC phenomenon suggests that rising income levels increase economic activity and reduce environmental quality. The connection between FDI and economic growth is, however, still controversial, with theories suggesting that FDI boosts domestic capital, creates jobs, and promotes technology; however, it may also contribute to global warming. Arthur et al. (2024) examined the relationship between FDI and sustainable development in 48 African economies from 1990 to 2020 and reported mixed results. A negative causal relationship was found, especially in low-income countries, while a positive effect was observed in high-income countries.

Other recent studies reveal that FDI harms the ability of emerging economies to develop sustainably. The economies of India, Turkey, and MENA support the pollution haven hypothesis, indicating that FDI negatively impacts the host country's sustainable development (Gorus and Aslan, 2019; Karimov, 2020; Rana and Sharma, 2020). For example, Sbia et al. (2014) argue that eco-friendly FDI strategies in developing countries can lead to low economic growth, resource depletion, ecological pollution, cultural changes, and stricter environmental requirements, which mitigate these negative impacts. Moreover, Bokpin (2017) reported that current trends strongly emphasize ecological sustainability and sustainable development, minimizing the necessity for antiquated technologies.

Trade openness promotes the free flow of goods and services. Despite conflicting findings on the effects of trade openness, the literature indicates that outward-oriented trade policies improve the economy and the standard of living (Shahbaz et al., 2013). Nevertheless, the effects of trade openness on a country's environment are contingent on its degree of industrialization and development. Developed countries have adopted cleaner production methods and better technologies to improve

environmental quality. However, developing economies may import low-cost and environmentally harmful technologies that cause environmental degradation (Destek and Sinha, 2020). Al-Mulali and Ozturk (2015) reported that trade freedom, together with variables such as energy consumption, goods production, stable politics, and rural–urban mobility, significantly affects the sustainability of MENA countries. According to Al-Mulali et al. (2015, 2016), trade liberty has a beneficial effect on the ecological sustainability of lower- and upper-middle-income countries.

With respect to the econometric techniques used in these studies, Chishti and Patel (2023) highlight a critical gap in the literature showing that traditional econometric techniques can produce contradictory results between climate change and sustainable development because of their failure to adequately address complex econometric issues. Standard methods often overlook these complexities, resulting in erratic and biased outcomes. To address this gap and gain a deeper understanding of how various parameters influence sustainable development, more advanced approaches, such as quantile ARDL, quantile-on-quantile models, and Granger causality, which offer more robust and nuanced insights, are needed. Notably, most related studies have focused on groups of countries, such as the BRICS (Baloch and Wang, 2019) and the G-7 (Gu et al., 2020), the OECD (Mensah et al., 2018; Ulucak and Ozcan, 2020), and some developing countries, such as Pakistan (Hassan et al., 2019) and China (Ahmed et al., 2020; Y. Sun et al., 2008). However, to our knowledge, no research has been conducted in the context of the GCC countries, which are rich in natural resources, mainly oil and gas.

Similarly, the current body of research on climate change, technological advancements, urban development, and sustainability primarily relies on global or non-GCC-specific investigations, which limits its relevance to the distinct socioeconomic and environmental circumstances of the GCC region. For example, a significant portion of studies on transitions to renewable energy concentrates on developing economies with established institutional structures and diverse economies (Jacobsson and Johnson, 2000; Younis et al., 2021). Although these studies provide valuable perspectives on general patterns, they do not account for the resource-dependent characteristics like the GCC economies, where oil revenues constitute a major portion of GDP, institutional capacities differ, and environmental policies often provide a backseat to economic objectives. Furthermore, commonly applied theoretical frameworks, such as the Environmental Kuznets Curve (EKC) and the Pollution Haven Hypothesis (PHH), are not consistently tested in resources-rich, rentier states, like those in the GCC. Regional analyses, including those by Kahouli and Chaaben (2022) and Rafindadi et al. (2018), make significant contributions by examining the environmental consequences of trade liberalization and FDI in GCC countries; however, they frequently overlook the crucial role of financial mechanisms and technological innovation in achieving long-term sustainability.

2.2. Literature gaps

This research gap emphasizes the necessity for GCC-specific studies that combine economic, environmental, and financial aspects, particularly considering the region's ambitious renewable energy goals and reliance on hydrocarbons. Addressing these shortcomings is crucial for developing actionable, regionally tailored policies that align with both the global sustainability objectives and the unique challenges faced by the GCC. This research aims to contribute to the existing knowledge by providing a comprehensive and regionally focused analysis of the intricate interplay between climate change, urbanization, technological innovation, natural resources, and sustainable development within the GCC economies. It highlights the critical importance of how climate change, FDI, trade openness, technological innovation, and natural resources affect sustainable development in the GCC economies over various periods. Through this approach, the investigation not only fills a significant gap in the current literature but also provides practical guidance for policymakers and stakeholders in the region who endeavor

to achieve sustainability goals.

2.3. Theoretical framework

This research utilizes essential theoretical models to examine the connections between climate change, technological advancement, and sustainable development within the GCC nations. The Environmental Kuznets Curve (EKC) proposes that economic expansion initially causes environmental harm, but after surpassing a certain point, further growth results in environmental enhancements as economies transition to cleaner technologies (Ganda, 2022b). However, recent research, such as that by Dam et al. (2024), suggests that the EKC may not be applicable in all areas, especially in regions reliant on fossil fuels, such as the GCC, where economic growth is frequently associated with environmental damage. The Pollution Haven Hypothesis (PHH) argues that lenient environmental regulations draw industries that exploit natural resources, potentially obstructing sustainable development (Majeed et al., 2021). Nonetheless, studies in developing economies, such as the GCC, have yielded varied outcomes, with some indicating that FDI positively influences sustainable industries (Raman et al., 2024), while others point out adverse environmental effects (Usman et al., 2021). Finally, Institutional Theory highlights the importance of both formal and informal institutions in guiding sustainable development (Razzaq and Yang, 2023). For example, in the GCC, robust institutional frameworks can promote sustainability through policies that support renewable energy, although significant institutional barriers persist, as evidenced by differing findings between the GCC and OECD countries, where policies are typically more comprehensive and well integrated (Javaid et al., 2022). These frameworks provide a detailed understanding of the challenges and opportunities of GCC in pursuing sustainable development, especially when compared to regions with distinct resource management and institutional setups.

3. Data, models and methodology

3.1. Data and descriptive statistics

We use data for the GCC countries (Bahrain, Oman, Kuwait, Saudi Arabia, the UAE, and Qatar) from 2001 to 2020 to evaluate the impact of climate change on sustainable development. The sample was selected while considering the UN’s SDGs 12, 13 and 17. For sustainable development, data were collected from J D Sachs et al. (2023), and the sustainable development index (SDI), a proxy for sustainable development, is taken as the dependent variable. Temperature (TEMP) is a proxy for climate change and is measured in degrees Celsius. Data on gross domestic product (GDP), foreign direct investment (FDI), trade (TRD), total population (TPP), and natural resource rents (NRS) were collected from the World Bank database. GDP, measured in 2010 USD, is used as a proxy for economic growth. FDI is measured as the net inflow of imports and exports as a percentage of GDP. Trade is a percentage of GDP, and technological innovation (TIP) is a proxy for the number of patents. All the variables are presented in Table A.1 in the appendix.

The statistical characteristics of the selected datasets are presented in Table A.2 in the appendix. The statistical data indicate that the total population has the highest mean, while GDP has the smallest mean. Furthermore, the average for each variable is positive, suggesting that, on average, the value of every variable increases over time. Moreover, there is a noticeable disparity between the minimum and maximum values of the selected series and a large variation in the series, which suggests that the dataset has a nonlinear distribution.

The Jarque–Bera test further verifies that the chosen series are non-normal because the p-value of each series is close to zero. The results of the skewness, kurtosis, and standard deviation tests suggests the same. Except for TEMP, which has negative skewness, all the variables show a positive skew. Kurtosis shows that most variables (SDI, TIP, TPP, FDI, GDP) have heavy tails, while only TEMP, TRD, and NRS have light tails

relative to the peaks in the dataset. In summary, the pre-estimation analysis confirms that the selected dataset has a non-normal distribution; nonetheless, the use of a linear estimator could lead to erroneous and incoherent outcomes (Naeem et al., 2023). A nonlinear estimator needs to be used to address the unequal distribution of the series. Therefore, the panel QARDL approach is useful for gathering reliable, fine-grained data and suggesting appropriate recommendations.

The pre-estimation findings indicate that the variables TEMP, TIP, FDI, GDP, TRD, and TPP have an important association with the dependent variable SDI. There is a negative correlation between SDI and FDI, NR (Fig. 1).

Fig. 2 shows a striking concentration of multiple indicators in the GCC, as evidenced by the deep blue color gradient. This concentration is particularly prominent on the left side, indicating that these countries present higher values for various metrics, including the SDI, TEMP, TIP, NRS, FDI, TRD, and TPP. For example, Saudi Arabia has substantial natural resource rents and a relatively large population. Similarly, countries with darker blue shades in the FDI graph, such as the UAE and Qatar, present significant foreign investment inflows, reflecting their strategic economic policies and openness to global markets. The areas in darker blue in the SDI panel present a stronger emphasis on achieving sustainability targets, driven by investment and economic diversification efforts as reported in Ben Mim and Ben Ali (2020). In general, the darker blue draws attention to economic inequalities within the GCC, where certain countries excel in various indicators, implying a need for tailored economic strategies to promote balanced development across the region.

3.2. Models and tests

In the realm of panel data analysis, the presumption that cross-sectional units are independent is crucial as it forms the basis for numerous econometric methods. Nonetheless, this assumption is frequently breached in real-world scenarios because of the shared influences or simultaneous shocks impacting several units, resulting in cross-sectional dependency (CSD). CSD arises when error terms are interrelated across different units, potentially skewing the statistical outcomes. Failure to verify this assumption can lead to incorrect standard errors, biased parameter estimates, and misleading conclusions. Recognizing and addressing CSD is vital for enhancing the reliability and robustness of panel-data models. By identifying and adjusting for CSD, researchers can improve the accuracy of their estimates, leading to more

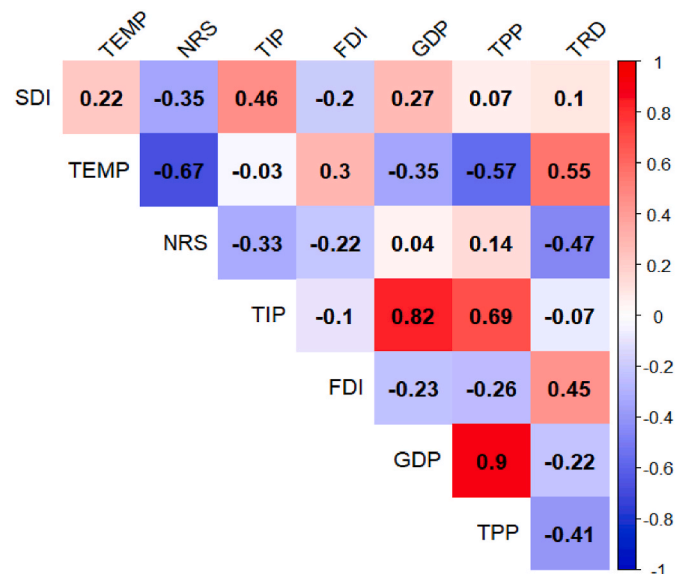


Fig. 1. Correlation visual statistics.

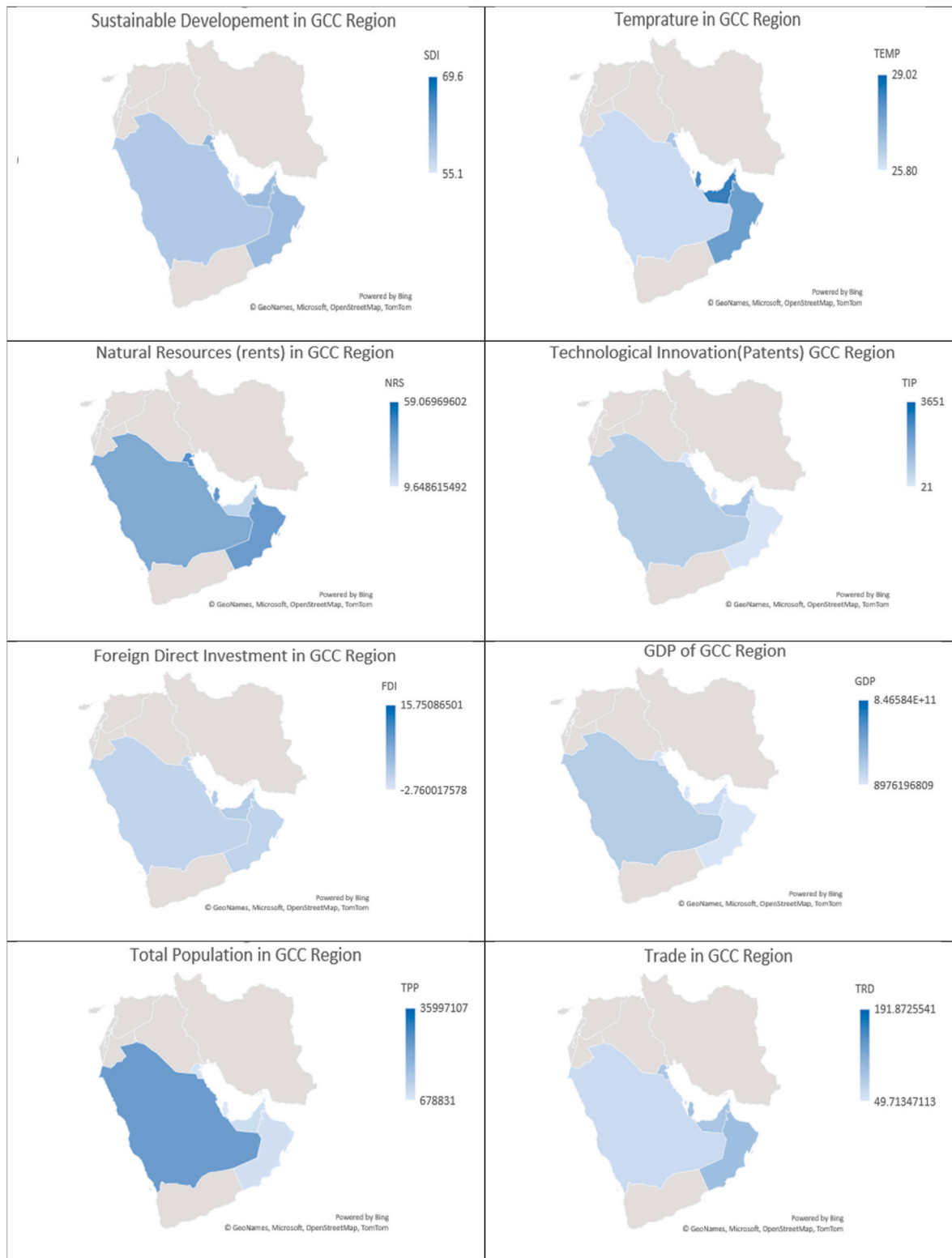


Fig. 2. Individual indicator map of GCC countries.

precise and credible statistical results. CSD in panel data models may be tested in numerous ways, such as the well-established CSD test by Pesaran et al. (2008) and the Breusch and Pagan (1980) Lagrange multiplier.

After conducting the CSD test, we investigated the slope uniformity within cross-sections, considering the varying economies and demographics of the GCC countries, and adopted the slope homogeneity

approach proposed by Pesaran (2004) via test-statistic formulae. The slope test was used to identify heterogeneity. The results of this test enable more robust econometric unit root and cointegration evaluation.

The reliability of the estimates was confirmed through unit root tests to determine the stationarity of the variables. Appiah et al. (2023) differentiated between the first-generation panel unit root tests and the second-generation unit root tests. The first generation of tests assumes

cross-sectional independence, while the second generation tests relax this assumption, allowing for CSD. Therefore, we employ second-generation unit root tests. According to Danish et al. (2019), the problem of homogeneity is reduced by the use of second-generation tests, such as the IM–Pesaran–Shin test, Fisher–ADF test, and Fisher–PP test. In addition, Pesaran (2007) introduces tests such as the cross-sectional Im, Pesaran and Shin (CIPS) and cross-sectional augmented Dicky Fuller (CADF) tests, which address CSD due to significant differences in SDI levels among GCC countries.

Scholars have employed various mathematical and econometric models to determine the relationships among TEMP, TIP, FDI, GDP, TRD, TPP, and SDI, and various perspectives have been offered (F. Sun et al., 2021). We selected the quantile autoregressive distributed lag (QARDL) model, which has been widely used in numerous other studies (Appiah et al., 2023; Cho et al., 2015). Cho et al. (2015) introduced this model to explore the equilibrium among predictor variables and quantiles of the criterion variable over an extended period (Appiah et al., 2023). As a robust technique, the QARDL model allows the examination of nonlinear linkages between economic variables, such as economic growth (GDP), natural resources, green technology, FDI, and SDI. We chose to apply the QARDL for analysis as it incorporates both long- and short-run relationships between the variables considered in this study. Unlike other conventional econometric models, the QARDL model can also determine the cointegration of variables at a single level of the dependent variable.

The QARDL model can evaluate and capture the nonlinear relationships across the different levels of the dependent variable (Afshan et al., 2023; Appiah et al., 2023). To further strengthen the robustness of the results of this study, the Wald test was also conducted with the aim of establishing the relationship between the dependent and independent variables. This supports the uniformity of the coefficient integration throughout the quantiles (Appiah et al., 2023) in the time series in the short run and the long run and influences the dependability of the parameter in each quantile.

Starting with the ARDL model, which has been widely applied by previous scholars, the first equation for this study is expressed as follows:

$$Y_t = a + \sum_i^p \beta_1 Y_{t-i} + \sum_i^q \beta_2 X1_{t-i} + \sum_i^r \beta_3 X2_{t-i} + \sum_i^s \beta_4 X3_{t-i} + \sum_i^t \beta_5 X4_{t-i} + \sum_i^z \beta_6 X5_{t-i} + \varepsilon_t \tag{1}$$

where ε_t denotes the error term, which explains the $Y_{t-i} - X[X_{t-i}/ F_{t-1}]$ represented by temperature (TEMP_t), natural resource rent (NRS_t), technological innovation (TIP_t), foreign direct investment (FDI_t), gross domestic product (GDP_t), total population (TPP_t), and trade (TRD_t) [TEMP_{t-1}, NRS_{t-1}, TIP_{t-1}, FDI_{t-1}, GDP_{t-1}, TPP_{t-1}, TRD_{t-1}]. Together, these are p, q, r, s, t, and z, which indicate the lag orders. On the basis of these variables, Eq. (1) can be transformed as follows:

To introduce the error correction model measure for the QARDL framework, Eq. [4] is as follows:

$$Q_{\Delta SDI_{2\tau}} = a(\tau) + \rho(\tau)SDI_{t-i} - \omega_1(\tau)TEMP_{t-i} - \omega_2(\tau)NRS_{t-i} - \omega_3(\tau)TIP_{t-i} - \omega_4(\tau)FDI_{t-i} - \omega_5(\tau)GDP_{t-i} - \omega_6(\tau)TPP_{t-i} - \omega_7(\tau)TRD_{t-i} + \sum_{i=1}^{p-1} \beta_1(\tau)\Delta CO_{2,t-i} + \sum_{i=0}^{q-1} \beta_2(\tau)\Delta TNR_{t-i} + \sum_{i=0}^{r-1} \beta_3(\tau)\Delta FDI_{t-i} + \sum_{i=0}^{s-1} \beta_4(\tau)\Delta ITR_{t-i} + \sum_{i=0}^{t-1} \beta_5(\tau)\Delta FA_{t-i} + \sum_{i=0}^{z-1} \beta_6(\tau)\Delta GDP_{t-i} + \varepsilon_t(\tau) \tag{5}$$

Table 1
CSD and SCH tests.

Test	Delta	p value
Pesaran’s test of CSD	5.152***	0.000
Slope homogeneity	5.670***	0.000
Slope homogeneity (adjusted)	7.645***	0.000

Source: Authors’ estimate, (2024) Note: ***, ** and * indicate significance at the 1 %, 5 % and 10 % levels, respectively.

where Δ denotes the GCC countries’ SDI levels, which are predicted on the basis of the cumulative short-term impact of the past values of the variables. A Granger causality test is performed to ascertain the direction of causality among the study variables (Troster, 2018).

The interplay between economies is shaped by both economic and noneconomic factors, resulting in shared and divergent objectives. For instance, the GCC operates as a free trade area, facilitating the smooth flow of products and services among member economies. Although every economy has its own sources of gas and oil, they all benefit from a steady international energy market. As a result, we conclude that the GCC economies are dependent on one another. Therefore, the Pesaran and Yamagata (2008) SCH test is applied to assess dependence. The results are displayed in Table 1.

Panel data analysis requires the determination of whether an independent variable’s slope is homogenous or heterogeneous across all observations. Ignoring this distinction could lead to misleading results and hinder economic conclusions. Testing the slope homogeneity/heterogeneity ensures reliable results and prevents misleading conclusions. The estimated values of the slope homogeneity check (SCH) and adjusted SCH (adjusted) proved to be highly statistically significant, confirming the homogeneity of the slope, as mentioned in the null hypothesis. Table 1 displays the results of the CSD and SCH tests to determine whether the groups of variables exhibit homogeneity or heterogeneity. The null hypothesis of cross-sectional independence is rejected because of the strong statistical significance of the variables in the dataset (Table 1). Thus, we infer that variations in a GCC country’s population, natural resource rent, technological innovation, gross domestic product, trade, and climate may impact other GCC countries.

The variables used in our study present CSD, and the slope is heterogeneous within the dataset group; therefore, the second-generation unit root testing approach is appropriate for our investigation, as determined by the SCH test (Pesaran, 2007). In light of this, the Levin, Lin and Chu; Im, Pesaran and Shin; ADF–Fisher; and PP–Fisher tests are computed in addition to the second-generation unit root tests, which comprise the cross-sectional augmented IPS (Im, Pesaran, and Shin) (CIPS) and cross-sectionally augmented Dickey–Fuller (CADF) tests. The empirical results (Table 2) show that all variables (SDI, TEMP, TIP, TRD, FDI, GDP, and NRS) present statistically significant estimates at I (0) via the CIPS and CADF tests. TPP is the only variable that yields statistically significant results when tested via the CIPS method. Consequently, the null hypothesis, which states that temporal variables have a unit root, is rejected. Thus, we conclude that all the variables are stationary at I (0).

Table 2
Unit root test.

	LL & Chu	Im, P&S	ADF - Fisher	PP - Fisher	CADF	CIPS
SDI	-3.347***	-2.626***	26.446***	58.184***	14.589***	12.109***
p value	0.000	0.004	0.009	0.000	0.000	0.000
TEMP	-6.266***	-6.461***	60.517***	484.321***	3.584***	3.610***
p value	0.000	0.000	0.000	0.000	0.011	0.005
TIP	6.098	-0.815	22.027**	64.144***	-3.495**	0.833***
p value	1.000	0.208	0.037	0.000	0.045	0.000
TPP	-0.946	-1.612**	18.713*	6.695	1.096**	5.691***
p value	0.172	0.054	0.096	0.877	0.062	0.000
TRD	-4.777***	-4.447***	42.124***	62.407***	21.536**	14.695***
p value	0.000	0.000	0.000	0.000	0.004	0.003
FDI	-2.061**	-3.772***	35.845***	86.859***	2.120***	0.946***
p value	0.020	0.000	0.000	0.000	0.000	0.000
GDP	-2.618**	-3.085***	29.528***	36.845***	3.299***	1.662**
p value	0.004	0.001	0.003	0.000	0.003	0.056
NRS	-6.195***	-4.452***	41.602***	47.201***	4.698***	7.142***
p value	0.000	0.000	0.000	0.000	0.012	0.000

Source: Authors' estimate, (2024) Note: ***, ** and * significant at the 1 %, 5 % and 10 % levels, respectively.

Table 3
Panel cointegration test.

Indicators	Gt	Ga	Pt	Pa
TEMP	-1.644**	-9.645***	-2.131***	-5.894***
NRS	-1.840**	-11.782***	-2.538***	-10.334***
TIP	-2.133**	-9.526***	-3.640***	-12.540***
FDI	-1.422*	-7.435***	-2.696***	-7.687***
GDP	-1.610**	-9.234***	-2.977***	-10.689***
TPP	-1.934**	-6.239***	-4.471***	-7.609***
TRD	-1.320*	-10.454***	-2.326***	-9.864***

Source: Authors' estimate, (2024) Note: ***, ** and * significant at the 1 %, 5 % and 10 % levels, respectively.

Statistical tests such as Pesaran's CSD, a test of stationarity, and cointegration tests are reliable and can accurately quantify stationarity, cross-sectional dependency, and long-term correlations. Additionally, panel estimation techniques are expected to adequately handle conditional heteroskedasticity, guaranteeing the stability of the estimated connections. These assumptions serve as the empirical underpinning of the study, which sheds light on the intricate interactions between numerous variables and sustainable development in the GCC economies.

Table 4
Results of Quantile Autoregressive Distributed Lag (QARDL) model for SDI.

Short-Run Estimations								
Quantile	Constant	TEMP	NRS	TIP	FDI	GDP	TPP	TRD
0.1	-0.3746***	-0.2265***	-0.1463***	0.733***	-0.2938***	0.3741***	-0.9318***	0.0161**
0.2	-0.1925**	-0.1557***	-0.215***	0.631***	-0.206***	0.5632***	-1.0417**	-0.058**
0.3	-0.1132***	-0.1739***	-0.3006***	0.5236***	-0.1816**	0.6951***	-1.1012**	-0.0728**
0.4	-0.0569**	-0.1955***	-0.3311***	0.5328***	-0.1488**	0.6741***	-1.0746**	-0.1087**
0.5	-0.0089*	-0.1612***	-0.3297***	0.4806***	-0.1291*	0.6893***	-1.0068**	-0.1109**
0.6	0.0836**	-0.1247**	-0.269***	0.5544***	-0.1464**	0.6532***	-1.0178**	-0.1116**
0.7	0.1648**	-0.0649*	-0.2438**	0.5558***	-0.1575**	0.5904***	-0.9493**	-0.1179***
0.8	0.2215***	-0.084*	-0.2481***	0.5511***	-0.1269**	0.6397***	-1.0003**	-0.098*
0.9	0.3865***	0.0753**	-0.1772**	0.5923***	-0.1213*	0.5157***	-0.8596**	-0.0992*
Long-Run Estimations								
0.1	124.1***	-2.339***	-0.083**	0.002***	-0.33***	0.003***	0.023***	0.012
0.2	85.48***	-1.003*	-0.008	0.002***	-0.353***	0.002*	0.054***	0.016
0.3	79.96***	-0.761	-0.011	0.002***	-0.328***	0.002	0.026***	0.012
0.4	75.76***	-0.529	-0.029	0.002***	-0.303***	0.006**	0.068***	0.001
0.5	68.76***	-0.264	-0.023	0.002***	-0.33***	0.008**	0.092***	-0.001
0.6	65.23***	-0.147	-0.008	0.002***	-0.291***	0.004**	0.042***	0.002
0.7	69.63***	-0.277	-0.016	0.002*	-0.293*	0.0001	0.032*	-0.002
0.8	65.23*	-0.049	-0.027	0.002	-0.0242	0.0008	0.002	-0.01
0.9	64.233*	0.373	-0.088	0.004**	0.155	0.0005	0.035**	-0.08***

Source: Authors' estimates (2024). ***, ** and * indicate significance at the 1 %, 5 % and 10 % levels, respectively.

Once the sequence of the integration of the variables has been established, a second-generation cointegration test is utilized. The QARDL model relaxes the assumption of classic ARDL models that the variables have a specific integration order, such as a combination of I (0)* and I (1). Even in cases in which all variables are stationary at I (0), the QARDL model can be used. According to the results displayed in Table 2, every variable is stationary at I (0) in the second-generation test. Therefore, our study verifies the panel cointegration test results of Westerlund (2008).

The estimation outcomes presented in Table 3 demonstrate considerable cointegration across the parameters, despite CSD. The cointegration analysis comprised the following four tests: the Gregory and Hansen (GT) test, the Gregory and Hansen test with added structural breaks (GA), the Phillips and Perron test (PT), and the Perron and Andrews (PA) test. The results presented in Table 3 imply that the dependent and independent variables are cointegrated at the 5 % level of significance.

A novel approach capable of managing autocorrelation and locational asymmetries is necessary for this investigation. Thus, we employ the panel QARDL model to assess the cointegrating relationship between variables, ensuring a stable long-term equilibrium relationship. The procedure entails determining whether short-term adjustments are

required to return the variables to a stable, long-term connection. The Wald test addresses the time-varying connection between variables and guarantees consistency in the integration of parameters within distinct quantiles.

4. Empirical results and discussion

4.1. Empirical results QARDL

The QARDL model estimation results reveals a long-term

relationship between sustainable development and various explanatory factors namely population, temperature, natural resources rent, technological innovation, GDP, FDI, and trade. The estimation outcomes presented in Table 4 specify the long- and short-term parameters. Temperature, natural resource rent, and FDI have significant negative impacts on all quantiles, suggesting that increases in these variables may impede sustainable development or create economic inefficiencies, regardless of the economic status of the entities under examination. Long-term relationships are crucial because of their long lasting effect in the GCC region.

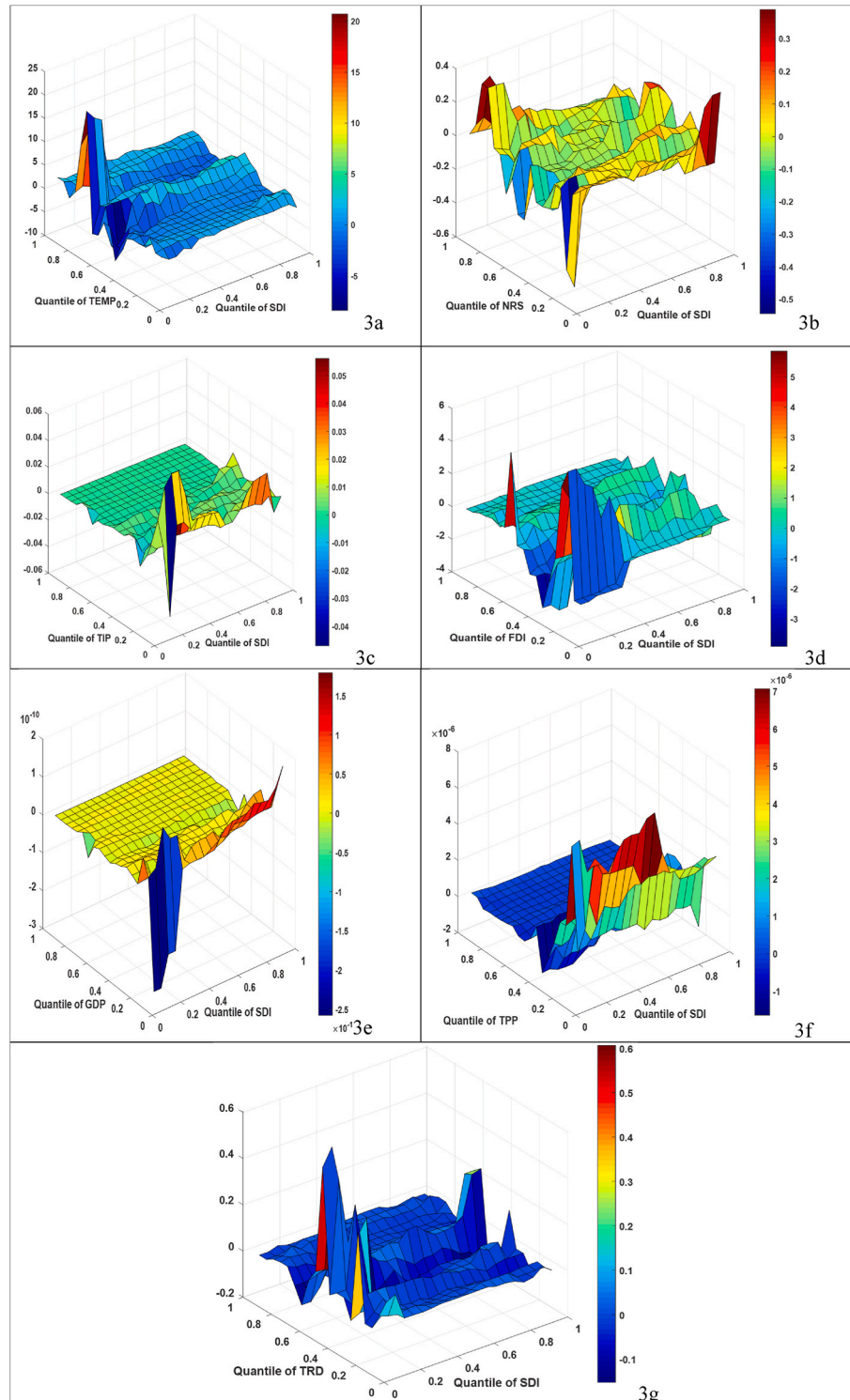


Fig. 3. Quantile-to-quantile relationships between TEMP, NRS, TIP, FDI, GDP, TPP, TRD and SDI.

The QARDL model shows that trade has a positive long-term coefficient and therefore impact on sustainable development up to a certain point, but a negative coefficient thereafter, indicating a turning point at which the negative impact of trade become more noticeable. Technological innovation, GDP, and population have no long-term impact on sustainable development because of the use of outdated technologies, resource-intensive growth, and limited investments in green technology. Population expansion can put pressure on available resources and infrastructure, while economic growth, as measured by GDP, may yield short-term benefits. Our estimation results also show the existence of a positive relationship between GDP and sustainable development, as higher incomes typically result in increased resources and energy consumption across various economic sectors (Amer et al., 2022).

4.2. Empirical results of Quantile on Quantile (QoQ)

The impact of temperature on SDI in the GCC countries is shown in Fig. 3a. The negative effects of temperature on the SDI at the lower quantiles (0.1–0.4) and middle quantiles (0.4–0.7) suggest that in regions or sectors with lower levels of development and moderate temperatures, increases in temperature may further hinder development, exacerbating negative outcomes such as resources scarcity and reduced productivity. Conversely, the small and positive slope coefficient in the higher quantiles of temperature (0.8–0.99) and lower quantiles of SDI (0.2–0.4) indicate that in less developed regions with higher temperatures, the adverse effects of temperature might diminish, possibly due to adaptive measures or the minimal additional impact on already stressed systems. However, the magnitude of this positive impact is small, indicating that while there may be some resilience or adaptation, it is not sufficient to drive significant development gains.

Fig. 3b illustrates the negative impact of natural resource scarcity (NRS) on SDI in the GCC economies, as indicated by a slope coefficient ranging from -0.6 to 0.3. This suggests that a greater scarcity of natural resources generally accompanies a lower level of sustainable development. However, the study also revealed that in the high NRS quantiles (0.90–0.95) and low SDI quantiles (0.1–0.2), the impact of the NRS score on SDI was positive but weak. Consistent with resources curse theory (Clootens and Ben Ali, 2021), the findings of Zhao and Rasoulinezhad (2023), Amer et al. (2022), and Alvarado et al. (2021) support our results. Similarly, Fig. 3c illustrates the impact of technological innovation on sustainable growth in the GCC countries, with the slope coefficient falling between -0.06 and 0.02. Although technology can enhance sustainability, its effect remains minimal in most scenarios. Similarly, TIP has a small but positive effect on SDI in the high (0.8–0.95) and the low quantiles (0.2–0.4), suggesting that in less developed regions or sectors, significant technological advancements can marginally improve sustainability outcomes, potentially through the adoption of more efficient or environmentally friendly practices.

Fig. 3d illustrates how FDI affects SDI in the GCC countries. The slope coefficient falls between -4 and 4, suggesting that FDI may often lead to outcomes that are not conducive to sustainable development, possibly due to investment in sectors with lower environmental standards or depletion of natural resources. The impact of FDI on SDI is negative across all quantiles (0.1–0.95) of the two measures. However, the positive and significant impact of FDI on SDI is more noticeable in the middle and upper quantiles (0.4 and 0.8) of FDI and the lower quantile (0.2) of SDI, indicating that in certain cases, particularly in less developed regions, moderate to high levels of FDI can drive improvements in sustainability, likely through the introduction of new technologies, infrastructure, or capital that enhance development outcomes. Nonetheless, this positive impact is nuanced and inconsistent, highlighting the complex relationship between FDI and sustainable development. The findings of Gorus and Aslan (2019) and Karimov (2020) align with our results.

Fig. 3e shows how GDP affects SDI. The slope coefficient falls between -2.5 and 2. In higher quantiles, GDP has no influence on SDI.

However, the effect of GDP switch from negative to positive in the lower GDP quantiles (0.2–0.3), and the range of SDI quantiles coefficient is 0.2–0.95. This ranging relationship from positive to negative indicates that initial economic growth has a limited influence on sustainable development due to the economic structure and governance systems. Fig. 3f also shows a negative to positive result related to the effect of population on SDI, suggesting that, as residents' purchasing power increases, so does their interest in renewable energy, leading to lower pollution levels.

Finally, Fig. 3g illustrates how trade affects SDI. The slope coefficient ranges between -0.2 and 0.6. Trade and SDI have a negative relationship across all quantiles (0.1–0.95) of the two variables, suggesting that increased trade may often be associated with lower levels of sustainable development, potentially due to the environmental degradation or social inequalities that can accompany trade expansion, especially in developing regions. However, trade has a stronger positive effect on SDI at the lower (0.2–0.4) and higher (0.75–0.8) quantiles of SDI, indicating that in less developed regions or in cases where trade is more developed, trade can contribute positively to sustainability. However, this modest effect highlights the need for complementary policies and related investments to maximize the benefits of technological innovation for sustainable development. Similar results were reported by (Alvarez-Herranz et al., 2017; Javaid et al., 2022; Mensah et al., 2018) reported similar results. Fig. 3d shows how FDI affects SDI in GCC countries, with a slope coefficient ranging between -4 and 4.

4.3. Robustness test: Granger causality

The Granger causality test results presented in Table 5, provide further insights into the relationships between the selected independent variables and SDI. Significant bidirectional causalities ($p \leq 0.01$) were observed from TIP, TPP, and GDP to SDI, and vice versa. One-way causalities were also observed among temperature, FDI, NRS, trade, and SDI. The results demonstrate that FDI inflows, natural resource extraction, and trade policies significantly influence sustainability outcomes in the GCC economies, highlighting the interconnected dynamics of the economic and environmental variables.

4.4. Discussion on results

The results reveal several critical insights into the sustainability challenges faced by the GCC economies. The significant negative impact of temperature, natural resources rent, and FDI on sustainable development underscores the vulnerability of the region to climate change and resources mismanagement. The GCC countries face compounded challenges, such as rising temperatures, water scarcity, and over-extraction of natural resources, which hinder their ability to achieve

Table 5
Tests for Granger causality.

Null hypothesis	F	p value	Inference
TEMP ⇌ SDI	2.2772**	0.0228	TEMP → SDI
SDI ⇌ TEMP	1.5885	0.1122	SDI # TEMP
NRS ⇌ SDI	2.4413**	0.0590	NRS → SDI
SDI ⇌ NRS	1.1518	0.8794	SDI # NRS
TIP ⇌ SDI	4.3720***	0.0000	TIP ↔ SDI
SDI ⇌ TIP	3.2280***	0.0012	SDI ↔ TIP
FDI ⇌ SDI	1.9436**	0.0454	FDI → SDI
SDI ⇌ FDI	0.3454	0.5859	SDI # FDI
GDP ⇌ SDI	6.5331***	0.0000	GDP ↔ SDI
SDI ⇌ GDP	4.5448***	0.0000	SDI ↔ GDP
TPP ⇌ SDI	9.5836***	0.0000	TPP ↔ SDI
SDI ⇌ TPP	7.3067***	0.0000	SDI ↔ TPP
TRD ⇌ SDI	2.4825***	0.0130	TRD → SDI
SDI ⇌ TRD	1.7492*	0.0803	SDI ↔ TRD

Note: → represents a one-way effect; ↔ represents a two-way effect; # represents no effect; *, **, and *** signify levels at 1 %, 5 %, and 10 %, respectively.

SDGs related to clean water, sanitation, and climate action (Alahmad et al., 2022; Haque and Khan, 2022). The detrimental effects of increasing temperatures on sustainable development are linked to the region's harsh climate characterized by high heat and limited water availability, which are already major issues. These climatic conditions have a direct impact on agricultural output, water supply, and energy needs, all of which play a role in shaping sustainable development results. For example, rising temperatures increase the demand for cooling systems, leading to greater energy use and potentially overburdening the energy infrastructure, thereby diminishing the overall sustainability. The industrial framework of many GCC economies is predominantly based on oil and gas extraction, petrochemicals, and energy-intensive industries. These sectors are especially susceptible to climate change as they often encounter increased operational expenses due to higher temperatures, growing energy requirements, and environmental regulations. The significant reliance on fossil fuels also results in a larger carbon footprint for the region, further complicating the efforts to achieve sustainable development. This connection between industry and climate highlights the necessity of diversification and adaptation strategies to lessen the effects of climate change. Overreliance on natural resources and FDI inflows into the oil and gas industries often prioritize short-term profits, exacerbate environmental degradation, and impede long-term sustainability (Mahmood, 2023). These findings support the resources curse theory, which argues that economies rich in natural resources often struggle to achieve sustainable development due to governance weaknesses and environmental challenges (Baloch and Wang, 2019; Hassan et al., 2019); Ulucak and Ozcan (2020).

Trade has both positive and negative impacts on sustainability. When accompanied by robust environmental policies, trade openness can improve sustainability by facilitating access to green technologies and encouraging innovation. For example, Oman's green hydrogen strategy represents a promising effort to leverage trade for sustainability, although it requires enhanced governance and policy support to realize its full potential. Similarly, technological innovation exhibits mixed impacts on SDI, suggesting that while new technologies have the potential to enhance sustainability, their effectiveness depends on complementary policies, infrastructure, and investment in green technologies.

Population growth and GDP also have mixed impacts on sustainable development, reflecting the conflictual relationship between economic expansion and pressure on resources. Urbanization and rising incomes in the GCC have contributed to increased energy consumption, posing environmental challenges. However, these factors can drive sustainability under certain conditions mainly with a renewable energy driven economic growth or when urbanization enhances infrastructure efficiency. These nuanced relationships highlight the importance of balancing the economic and the environmental priorities in policy design (Vardon et al., 2016).

The trade openness in the GCC countries can improve environmental quality and reduce CO₂ emissions by supporting the export of green technologies through carbon neutrality development. This leads to increased competitiveness and technological efficiency. Notably, countries such as the UAE, Oman, and the KSA have signed Memoranda of Understanding to partner in green hydrogen production, leveraging their land availability and renewable potential. In its green hydrogen strategy, Oman aims to increase hydrogen exports by 2050 by combining a net zero strategy and an industrial policy to create a new export industry and ecosystem. These results suggest that trade openness, GDP, and population growth can improve sustainable development (Kurniawan and Managi (2018); Y. Sun et al. (2008); and Were (2015).

Ultimately, the findings underscore the importance of integrated policy approaches that address the unique challenges faced by the GCC economies. A focus on renewable energy development, improved resource governance, and sustainable trade practices is critical for overcoming the environmental and economic vulnerabilities identified in this study. By aligning financial and governance systems with

sustainability targets, GCC countries can make significant strides toward achieving long-term development goals, while mitigating the negative impacts of climate change and resource dependency.

5. Conclusions and policy implications

5.1. Concluding remarks

This study employs a QARDL estimation technique, which includes quantile-on-quantile and Granger causality tests, to assess the intricate interplay between climate change, technological innovation, trade, natural resources, FDI, population and GDP and sustainable development. The estimation outcomes for the GCC countries suggest that sustainability is not influenced in the long run by technological innovation, GDP, or population size. However, FDI, which lacks sufficient environmental considerations, intensifies industrial carbon emissions and contributes to elevated temperatures, thus adversely affecting sustainable development. Furthermore, the dynamic results of the quantile-on-quantile approach confirm the empirical findings of the QARDL model. The empirical results for the short run indicate that temperature negatively affects sustainable development in most quantiles, indicating that temperature increases can reduce sustainable development outcomes. Negative effects are observed across several quantiles, particularly in the middle quantiles (e.g., 0.3 to 0.7), implying that greater natural resource dependency might hinder short-term sustainability. Technological innovation consistently has positive effects across all quantiles, indicating its role in enhancing sustainable development.

Although rising temperatures become less severe over time, negative effects are still noticeable, particularly for lower-income groups. Similarly, the negative effects of natural resources decrease over time, but some harmful impacts remain, particularly for groups with the lowest income levels. This implies that economies with strong dependence on natural resources may still encounter difficulties, even as overall economic conditions show signs of improvement. The influence of technological innovation remains consistent and positive, reinforcing its crucial role in long-term sustainability. The negative impact of FDI in the short run persists in the long run, particularly in lower quantiles, indicating that FDI may not always be beneficial for long-term sustainability in the absence of appropriate regulatory frameworks. The positive relationship between GDP and the SDI continues in the long run, emphasizing the importance of sustained economic growth for sustainable development. The effects of population expansion and trade on long-term sustainable development differ across quantiles, with some showing notable positive effects. This finding indicates that the relationships among population dynamics, trade, and sustainability are inconsistent across all sectors. The influence of these factors may fluctuate over time and be influenced by changes in economic conditions, demographic shifts, and evolving trade patterns. This could result in diverse sustainability outcomes for different segments of the economy.

The mixed effects of trade on sustainable development are negative in the short term but positive in the long term, highlighting the need for well-crafted trade policies. Such policies should aim to enhance economic resilience while simultaneously encouraging sustainable practices, mitigating short-term economic disruptions from trade and maximizing long-term benefits. For example, trade can promote sustainability by facilitating access to green technologies and promoting efficient resource use. However, careful management is needed to mitigate short-term economic disruptions.

5.2. Policy implications and study limitations

To comprehend the economic effects of climate-related issues, it is necessary to implement policies that aim to reduce the vulnerability of industries reliant on natural resources and encourage the adoption of climate-resilient technologies. Essential measures include investing in renewable energy, enhancing energy efficiency, and advancing water

management technologies to counteract the adverse effects of climate change. Additionally, expanding the industrial base to reduce reliance on fossil fuels is crucial to mitigate the long-term effects of increasing temperatures on sustainable development in the region. Our study’s findings indicate that GCC countries should update their policy frameworks to better align sustainability with their economic planning and focus on diversification, technological innovation, and sustainable investment. Strengthening cooperation and transparency in sustainability reporting is crucial for promoting accountability and achieving the SDGs (Ben Ali and Lechman, 2024). By aligning economic strategies with sustainability objectives, GCC economies can minimize their environmental impacts and support global sustainability efforts. GCC economies must diversify beyond natural resources dependence and investigate other sectors.

Policies that promote economic diversification can support long-term growth and environmental sustainability. Regulations should be established to ensure that foreign direct investment complies with environmental standards, minimizing negative impacts on sustainability. It is therefore essential to promote green foreign direct investment in sectors such as renewable energy and environment-friendly infrastructure. Also, the GCC countries should adopt trade policies that enhance sustainability, including agreements that facilitate the export of green technologies. To address the environmental challenges caused by rising temperatures, it is necessary also to implement regional climate adaptation strategies such as improved water management and renewable energy solutions.

This study utilizes the aggregated data for the GCC countries, which may not capture country-specific shades and homegrown specificities. Given the diverse effects observed in various nations, it is essential to craft specific policy measures tailored to the distinct challenges and opportunities faced by each economy. For example, countries with advanced technological infrastructure can gain from policies that enhance green technology innovations and boost renewable energy export opportunities. Conversely, nations that depend heavily on oil exports may focus on policies that encourage energy transition technologies and promote economic diversification. Policymakers can create more effective and tailored strategies for sustainable development by considering unique national contexts.

Appendices.

Table A.1
Description of variables.

Variables	Description	Unit of Measurement	Source
SDI	Sustainable development index	Index	Jeffrey D Sachs et al. (2023)
TEMP	temperature as a proxy for Climate change	Annual mean temperature in centigrade	www.climateknowledgeportal.worldbank.org
TNR	Total natural resource rent	% of GDP	www.wdi.com
TIP	Technological innovation (patents)	Number	www.wdi.com , OECD and WIPO
GDP	Gross domestic product	Constant 2010 US\$	www.wdi.com
FDI	Foreign direct investment	Net inflow of imports and exports	www.wdi.com
TRD	Trade	Percent of GDP	www.wdi.com
TPP	Population	Total population	www.wdi.com

Table A.2
Descriptive statistics and correlation matrix.

Static indicators	SDI	TEMP	TIP	TPP	TRD	FDI	GDP	NRS
Mean	60.90091	27.55158	633.725	7630434	108.3827	2.237047	1.92E+11	31.49198
Median	60.823	27.8	273	3043591	98.0115	1.522891	1.15E+11	29.53191
Maximum	69.63078	29.02	3651	35997107	191.8726	15.75087	8.47E+11	59.0697
Minimum	55.10265	25.8	21	678831	49.71347	-2.76002	8.98E+09	9.648615

(continued on next page)

To gain a deeper understanding of the variations identified in this study, future research should focus on more detailed analyses through cross-country comparisons or case studies specific to individual countries. This approach would help clarify how factors such as technological innovation, trade openness, and climate change uniquely impact sustainable development in the GCC economies. Such insights would be invaluable for policymakers, enabling them to tailor strategies to address the distinct needs and challenges of each nation within the region. Further studies should examine the individual GCC economies to obtain more comprehensive findings. Despite employing robust methodologies to address potential endogeneity, unobserved factors may still influence the relationship between sustainable development and independent variables. Future research could use machine learning models to address this issue.

CRedit authorship contribution statement

Alanoud Al-Maadid: Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition. **Mohamed Sami Ben Ali:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition. **Ijaz Younis:** Writing – original draft, Visualization, Software, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table A.2 (continued)

Static indicators	SDI	TEMP	TIP	TPP	TRD	FDI	GDP	NRS
Std. Dev.	2.88723	0.94903	777.0499	10121396	31.00853	2.727322	2.08E+11	12.40309
Skewness	0.640573	-0.495749	2.15658	1.743839	0.811177	1.675834	1.600087	0.25625
Kurtosis	3.646893	1.913615	7.763739	4.506072	2.845818	7.577728	4.760974	2.0992
Jarque-Bera	10.29903	10.81651	206.4828	72.16074	13.27903	160.9463	66.71071	5.37049
Probability	0.005802	0.004479	0.000	0.000	0.001308	0.000	0.000	0.068204
Sum	7308.109	3306.19	76047	9.16E+08	13005.92	268.4457	2.31E+13	3779.037
Sum Sq. Dev.	991.9957	107.1782	71852984	1.22E+16	114421.9	885.1557	5.16E+24	18306.57
Observations	120	120	120	120	120	120	120	120

Data availability

Data will be made available on request.

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