

Article

Environmental Degradation in Gulf Cooperation Council: Role of ICT Development, Trade, FDI, and Energy Use

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Abstract: Environmental degradation is a pressing issue, particularly in resource-dependent regions like the Gulf Cooperation Council (GCC) countries. While significant research has explored the environmental impacts of economic growth and resource use globally, limited attention has been given to the unique dynamics in the GCC, including the role of ICT development, trade openness, and FDI inflows. This research examines how information and communication technology (ICT) development, economic growth, trade openness, foreign direct investment (FDI) inflows, and electricity consumption influenced environmental degradation in GCC countries from 1990 to 2022. Using panel data analysis, the study finds that ICT expansion and increased electricity consumption significantly contribute to higher CO₂ emissions, exacerbating environmental degradation. Economic growth follows the Environmental Kuznets Curve (EKC) pattern, where environmental harm initially increases with growth but can decline as economies diversify and adopt cleaner technologies. Trade openness and FDI inflows, particularly in resource-intensive industries, also contribute to environmental degradation, supporting the pollution haven hypothesis. However, these factors present opportunities for sustainable development if paired with stricter environmental regulations and cleaner technology adoption. The study highlights the need for GCC policymakers to prioritize renewable energy investments, enforce stronger environmental policies, and promote energy efficiency to balance economic growth with environmental sustainability. Recommendations for future research include exploring other environmental factors and assessing the role of technological innovations in reducing emissions.

Keywords: ICT development; economic growth; trade openness; FDI inflows; electricity consumption; environmental degradation; GCC countries; CO₂ emissions; Environmental Kuznets Curve (EKC); renewable energy

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1. Introduction

Environmental degradation is a major global challenge with widespread effects on ecosystems, human health, and economic sustainability. The Gulf Cooperation Council (GCC) countries—Saudi Arabia, Kuwait, Oman, Qatar, Bahrain, and the United Arab Emirates—are particularly susceptible due to their economic structure, which is heavily reliant on hydrocarbon exports. Over the past few decades, these countries have experienced rapid economic growth, resulting in heightened pollution, resource depletion, and

greenhouse gas emissions, all of which intensify environmental degradation [1]. Although these nations have made efforts to diversify their economies and reduce fossil fuel dependency, they continue to face significant obstacles in aligning economic growth with environmental sustainability. Environmental degradation is measured using carbon dioxide (CO₂) emissions per capita, which serve as a widely recognized indicator of environmental harm. CO₂ emissions capture the cumulative impact of industrial activities, energy consumption, and transportation on the environment, making them a reliable proxy for assessing environmental degradation. This measure is particularly relevant for Gulf Cooperation Council (GCC) countries, where energy-intensive industries and fossil fuel dependence are dominant contributors to environmental challenges. By focusing on CO₂ emissions, this study provides a clear and quantifiable perspective on the drivers of environmental degradation in the region.

Information and communication technology (ICT) has become a central force in economic transformation within the GCC. While ICT can enhance resource efficiency and drive innovation, it also escalates energy consumption and electronic waste, adding to environmental pressures [2]. Likewise, trade openness and foreign direct investment (FDI) have spurred economic growth and modernization in the region, but they also present environmental challenges, as they may lead to an influx of resource-intensive industries and technologies. Additionally, high electricity consumption in the region, largely generated from fossil fuels, significantly impacts the GCC's environmental footprint [3]. Gaining a comprehensive understanding of these factors' impact on environmental degradation is essential for formulating policies that support sustainable development in the GCC.

The economic growth of GCC countries, fueled by ICT expansion, FDI inflows, trade liberalization, and rising electricity consumption, has resulted in substantial environmental impacts. The region's dependence on energy-intensive industries and the adoption of modern technologies have accelerated environmental degradation, primarily through increased carbon emissions and resource depletion. For example, expanding energy use in the ICT and industrial sectors has led to larger material footprints across the GCC [2]. Additionally, while FDI and trade have facilitated economic modernization, they have also contributed to environmental harm by establishing polluting industries [1]. The GCC's reliance on non-renewable energy for electricity production exacerbates environmental issues, underscoring the need for a thorough evaluation of factors driving environmental degradation in the region.

This study seeks to evaluate the effects of ICT development, economic growth, trade openness, FDI inflows, and electricity consumption on environmental degradation in the GCC countries from 1990 to 2022. The findings have critical implications for policymakers, researchers, and environmental advocates in the GCC. As these countries pursue sustainable development goals, including those in initiatives like Saudi Arabia's Vision 2030, understanding the environmental impacts of ICT growth, economic expansion, trade, FDI, and energy use becomes essential. This study will provide empirical evidence to guide policies aimed at fostering environmentally sustainable economic growth. Additionally, the research adds to the global discussion on transitioning resource-dependent economies toward greener, more sustainable growth models, offering insights applicable beyond the GCC [3]. The motivation for this study stems from the unique environmental and economic challenges faced by the GCC countries. These nations are heavily reliant on fossil fuels and resource-intensive industries, which contribute significantly to environmental degradation. Despite their global economic importance, the GCC countries have received limited attention in the literature regarding the interactions between economic growth, ICT development, trade openness, FDI, and energy consumption on environmental outcomes. This study seeks to fill this gap by providing a comprehensive analysis of these

factors, aiming to contribute to the broader discourse on sustainability and the environmental implications of economic activities in resource-dependent regions

2. Literature Review

2.1. Environmental Degradation

Environmental degradation in GCC countries has become a significant concern, driven by rapid industrialization, urbanization, and economic development primarily fueled by oil and gas exploitation. Theoretical perspectives on environmental degradation often highlight the trade-offs between economic growth and environmental sustainability, especially in resource-abundant regions like the GCC. The Environmental Kuznets Curve (EKC) hypothesis is commonly cited in this context, proposing that environmental degradation rises in the initial stages of economic growth but eventually decreases once a nation reaches a certain wealth threshold and begins to adopt sustainability measures [2].

Recent research has examined multiple dimensions of environmental degradation in the GCC, with particular attention to pollution, resource depletion, and ecosystem disruption. For example, ref. [4] investigated the effects of environmental, social, and governance (ESG) practices on firms in the GCC. They found that, while ESG policies are increasingly adopted, the region's heavy dependence on fossil fuels still drives considerable environmental challenges, especially within the energy and industrial sectors. This study underscores the need for robust regulatory frameworks and corporate accountability to effectively address persistent environmental degradation in the GCC.

In the marine environment, ref. [5] investigated the environmental challenges impacting fisheries in the Arabian Gulf, identifying habitat degradation and pollution as primary threats to biodiversity. The author emphasized that unsustainable fishing practices and the destruction of marine ecosystems, often driven by economic activities like oil extraction and urban development, pose long-term risks to the Gulf's marine biodiversity.

Additionally, sediment management and its environmental implications were examined in a study by [6], which addressed the significant issue of sediment displacement in the Gulf of Oman and its effects on coastal ecosystems. The research demonstrated that climate change, alongside infrastructure development, disrupts natural sedimentation processes essential for ecosystem health in the region.

Several studies have extensively analyzed the relationship between economic growth, energy consumption, trade, and environmental degradation. For instance, research in China has demonstrated that rapid industrialization and urbanization significantly contribute to carbon emissions, with studies emphasizing the importance of renewable energy adoption and stricter environmental policies to mitigate these effects [7,8]. Similarly, in the United States, studies have shown that economic diversification and investment in clean energy technologies have been critical in reducing carbon emissions while maintaining economic growth [9,10]. While these studies provide valuable insights into global environmental dynamics, they often overlook the unique context of Gulf Cooperation Council (GCC) countries, where heavy dependence on fossil fuels, high energy consumption, and trade-intensive economies pose distinct environmental challenges. This study aims to address this gap by focusing on the GCC region, which remains underexplored in the environmental literature despite its critical role in global energy markets.

Despite these persistent environmental challenges, efforts in the GCC to combat degradation have been inconsistent. The region's heavy dependence on fossil fuels and water-intensive industries, combined with high energy consumption, continues to place strain on its vulnerable ecosystems. However, new policies supporting renewable energy and green technologies are being implemented as part of broader initiatives to align with global sustainability goals [3].

2.2. ICT and Environmental Impact

The expansion of ICT in the Gulf Cooperation Council (GCC) countries has been both an economic catalyst and a source of environmental concern. As digital transformation accelerates, particularly through the proliferation of data centers, telecommunications infrastructure, and smart technologies, the environmental costs are becoming increasingly evident.

A major environmental concern in the GCC's ICT sector is the substantial energy consumption required to operate networks and data centers. A study by [11] links technological advancement, urbanization, and economic growth to significant increases in CO₂ emissions, highlighting the environmental costs of energy-intensive systems reliant on non-renewable energy sources. Similarly, ref. [12] discusses the broader environmental consequences of ICT development, noting its dual potential to mitigate or exacerbate environmental degradation depending on implementation. While ICT can enhance resource efficiency and reduce energy waste through smart technologies, inadequate e-waste management and unsustainable practices in data handling amplify its environmental impact. The rapid adoption of digital infrastructure in the GCC has led to a surge in e-waste production, which poses challenges for recycling systems often unable to manage ICT product disposal effectively. Both studies propose solutions, including renewable energy integration within ICT infrastructure and the adoption of green ICT policies emphasizing energy efficiency, sustainable resource use, and improved e-waste recycling programs.

The role of ICT in shaping both economic development and environmental sustainability has been increasingly scrutinized in recent years. While ICT has catalyzed economic growth and digital transformation in the GCC countries, its environmental impact is becoming more evident. As ICT infrastructure expands, its energy requirements increase, contributing to higher carbon emissions and environmental degradation. Understanding how ICT affects the environment is critical for crafting policies that maximize its benefits while minimizing its ecological footprint.

2.3. Economic Development and Environmental Sustainability

The GCC countries have experienced rapid economic development, primarily driven by their extensive oil and gas reserves. However, this growth has come with considerable environmental costs. The central challenge for the GCC is to sustain economic growth while ensuring environmental sustainability—an increasingly critical balance as global environmental concerns intensify. This section explores the complex relationship between economic development and environmental sustainability in the GCC, drawing on key studies.

Economic growth in the GCC, driven by hydrocarbon extraction and export, has resulted in high carbon emissions and environmental degradation. The Environmental Kuznets Curve (EKC) hypothesis suggests that environmental harm initially rises with economic growth but eventually declines as economies mature and adopt cleaner technologies, as investigated by [13]. Despite their wealth, the GCC countries remain heavily reliant on fossil fuels, emphasizing the need for energy diversification and sustainable practices. A study by the International Monetary Fund (IMF) [14] highlights the region's efforts to reduce hydrocarbon dependency, emphasizing diversification into sectors like tourism, finance, and renewable energy. While progress has been made, further efforts are needed to implement policies that reduce carbon emissions and support environmental sustainability.

A crucial element of the GCC's strategy for balancing economic growth with environmental sustainability lies in developing renewable energy projects. A detailed case study on Masdar City, Abu Dhabi's carbon-neutral initiative, as an innovative example of renewable energy policy in the Gulf, was provided by [15]. This study emphasizes the

importance of investments in solar energy and sustainable urban planning in reducing the region's carbon footprint. However, [15] cautioned that, while initiatives like Masdar City are promising, their current scale is insufficient for fully shifting the region away from fossil fuel dependency. Expanding such projects and integrating renewable energy across various sectors will be essential for the GCC to meet its sustainability goals.

Moreover, incorporating renewable energy into the GCC's economic framework is vital for reducing carbon emissions and mitigating the environmental impact of economic expansion. The relationships between economic growth, renewable energy use, CO₂ emissions, and trade openness in BRICS countries, offering insights applicable to the GCC, were analyzed by [16]. Their findings indicate that renewable energy is instrumental in decoupling economic growth from environmental degradation. For the GCC, this suggests that heightened investment in renewable energy, coupled with trade openness policies, can drive both economic and environmental gains. Embracing renewable technologies and adopting cleaner trade practices are thus critical steps toward sustainability.

However, the relationship between energy consumption and economic growth remains a significant factor in the GCC's environmental sustainability. The energy–GDP relationship in the GCC, using panel data to assess causality, was examined by [17]. His study revealed that energy consumption is a key driver of economic growth in the region, posing a sustainability challenge due to the heavy reliance on fossil fuels. The findings underscore the urgency for the GCC to transition to sustainable energy sources, breaking the link between energy use and environmental degradation. This shift is essential to reduce the environmental impacts of economic growth and ensure long-term economic resilience.

2.4. Trade Openness and Environmental Quality

Trade openness has been a driving force behind the economic development of the GCC countries, promoting integration into global markets and fostering economic growth. However, the environmental consequences of this increased trade activity have become a critical concern. This section analyses how trade openness in the GCC affects environmental quality, focusing on the interplay between trade expansion, industrial growth, and environmental degradation.

Trade openness in the GCC has spurred the growth of resource-intensive industries, including petrochemicals, manufacturing, and energy production. These industries have driven significant economic growth. However, they have also added to environmental challenges, particularly in terms of rising carbon emissions and resource depletion. The increase in trade volume has allowed for greater industrial expansion, which often comes at a cost to the environment, particularly in regions heavily dependent on fossil fuels. However, trade is observed to have positive environmental impacts in OECD nations. Conversely, it negatively influences sulfur dioxide (SO₂) and carbon dioxide (CO₂) emissions in non-OECD countries, despite contributing to a reduction in biochemical oxygen demand (BOD) emissions within these regions [18–20].

The pollution haven hypothesis suggests that countries with less stringent environmental regulations may attract industries aiming to evade stricter standards in other regions. In the GCC context, ref. [21] investigated how trade openness has led to an influx of pollution-intensive industries, especially within the manufacturing and energy sectors. Their findings indicate that trade liberalization has supported the expansion of these industries, which has contributed to elevated pollution levels and environmental degradation in the region. The authors recommend that the GCC implement stricter environmental regulations to mitigate trade-related environmental harm.

Trade openness influences environmental quality in complex ways. It can worsen environmental degradation by supporting resource-intensive industries and the pollution

haven hypothesis, yet it also promotes the transfer of green technologies and the adoption of global environmental standards. This study examines these dynamics within the GCC, where trade openness significantly impacts economic growth and environmental outcomes. Despite these adverse environmental impacts, trade openness also presents opportunities for cleaner technology transfer. Trade can encourage the adoption of eco-friendly technologies and more efficient production processes, particularly in energy-intensive sectors, as suggested by [22]. In the GCC, trade agreements and foreign direct investment have enabled the import of energy-efficient technologies in fields such as construction and energy production, helping to reduce the region's carbon footprint. The widespread adoption of these cleaner technologies could help offset the environmental consequences of expanded trade if effectively integrated across sectors. Increased trade activity has further strained the GCC's natural resources. A study by [23] examined the link between trade openness and resource depletion, concluding that trade-driven industrial growth in the GCC has intensified the depletion of energy and water resources. The reliance on fossil fuels for both domestic use and exports, coupled with the region's high water consumption, has amplified challenges to environmental sustainability. Their study underscores the necessity for sustainable resource management practices to balance trade with environmental preservation. To address these challenges, the GCC must reinforce its environmental regulations related to trade openness. Likewise, ref. [24] advocated for embedding environmental standards into trade agreements to mitigate the ecological impact of increased trade. Their findings suggest that integrating environmental protections within trade policies can help curb pollution, encourage the adoption of cleaner technologies, and support economic growth without compromising environmental sustainability. Stricter environmental regulations are crucial for the GCC to balance the economic benefits of trade with environmental protection.

2.5. FDI and Environmental Degradation

Foreign direct investment (FDI) has been instrumental in advancing the economic development of the GCC countries. The influx of foreign capital has fueled industrial expansion, infrastructure growth, and broader economic diversification. However, the environmental impact of FDI remains a pressing concern. While FDI can facilitate technology transfer and support the adoption of cleaner technologies, it can also lead to environmental degradation, especially in cases where environmental regulations are lax or insufficiently enforced.

In developing economies, the environmental impacts of FDI have been widely debated. Proponents argue that FDI can introduce advanced, cleaner technologies and improve production efficiency, ultimately reducing environmental degradation. However, critics highlight the potential for FDI to exacerbate pollution and resource depletion, especially when foreign investors take advantage of weak environmental regulations in host countries. FDI inflows in developing economies, including the GCC, tend to correlate with higher carbon emissions and resource consumption due to increased industrial activity [25]. The authors suggest that the environmental impact of FDI largely depends on the regulatory framework of the host country and the type of industries attracting foreign investment.

The pollution haven hypothesis suggests that foreign companies may shift operations to countries with comparatively lenient environmental regulations, thereby contributing to higher pollution levels. In the GCC, FDI has largely been directed toward sectors like oil refining, petrochemicals, and heavy manufacturing, all of which are linked to substantial pollution. Studies by [26] indicate that FDI, especially in energy-intensive industries, is associated with increased CO₂ emissions. The primary rationale is that foreign investors are often attracted to the region due to its rich natural resources and relatively

relaxed environmental regulations, which allow them to operate with fewer environmental restrictions.

On a positive note, FDI can facilitate the transfer of environmentally friendly technologies, which helps to reduce the environmental impact of industrial activities. Moreover, ref. [22] investigated the role of FDI in promoting green technology transfer within the GCC and found that foreign firms in sectors like renewable energy and energy-efficient construction have contributed to lowering carbon emissions. The authors argue that FDI can serve as a valuable tool for advancing environmental sustainability, provided that host countries implement strong environmental policies that incentivize green investments.

The impact of FDI on environmental degradation largely depends on the regulatory framework of the host country. Robust environmental laws can align FDI with sustainability goals, but in the GCC, such regulations have traditionally been secondary to economic objectives. Strengthening emission standards, resource management policies, and conducting environmental impact assessments (EIA) for large projects are critical to mitigating the environmental risks of FDI. While FDI drives economic growth, particularly in resource-intensive sectors like oil and gas, it also contributes to pollution and resource depletion, supporting the pollution haven hypothesis. However, with robust regulatory frameworks, FDI can facilitate green technology transfer and support sustainable development.

2.6. Energy Consumption in the GCC and Its Environmental Impact

The GCC countries rank among the world's highest in per capita energy consumption, primarily due to their reliance on oil and gas. This high energy usage has created considerable environmental challenges, particularly through elevated CO₂ emissions. A study by [27] analyzed the impact of energy consumption on the environmental footprint of the GCC nations, revealing a substantial contribution of energy use to environmental degradation, marked by increased carbon emissions and resource depletion. The study emphasizes the urgent need for sustainable energy policies and the adoption of clean technologies to reduce these environmental impacts.

The relationship between economic growth, energy consumption, and environmental degradation is well-established in the GCC. Air pollution trends in Dubai were examined by [28], linking economic expansion and increased energy use to higher pollution levels. Their study demonstrates that while economic growth drives energy consumption, the resulting environmental impacts, such as increased air pollution, pose significant challenges to sustainability. The authors suggest that the GCC must balance its economic growth with sustainable energy consumption practices to mitigate these harmful effects.

One solution to mitigate the environmental impact of energy consumption is to adopt renewable energy sources and cleaner technologies. A study by [29] examined the dynamic relationship between clean energy use, environmental pollution, and economic growth in the GCC, stressing the need for investment in renewables, such as solar and wind power, to reduce fossil fuel dependency and lower carbon emissions. Clean energy contributes not only to mitigating environmental degradation but also to supporting long-term economic sustainability by reducing the strain on natural resources.

The environmental challenges stemming from high energy consumption in the GCC underscore the importance of implementing robust environmental policies. As economic growth continues, there is an increasing need for regulations that manage energy use and promote energy-efficient technologies. The implications of population growth, rising energy demand, and sustainability in the GCC, especially in the context of global climate change efforts, were explored by [30]. The study suggested that without stronger

environmental regulations, the adverse effects of energy consumption will continue to overshadow the economic gains of industrial growth.

Despite growing research on the environmental impacts in the GCC, several critical gaps remain. One major gap is the limited focus on effective environmental impact assessments (EIAs) in large-scale development projects, which are crucial for minimizing the environmental consequences of FDI and trade expansion. Additionally, while studies on renewable energy adoption are increasing, there is limited research on its long-term environmental and economic effects, raising questions about the sustainability and scalability of these initiatives. Furthermore, the role of technological innovation in reducing environmental degradation is underexplored, with few studies investigating which energy-efficient technologies could make the most significant impact. The EKC—which posits that environmental degradation initially worsens with economic growth before eventually improving—has also been inadequately studied in the GCC, especially given the region's dependence on fossil fuels. Research is similarly sparse on the social dimensions of environmental degradation, particularly its impact on public health and vulnerable populations. Lastly, cross-regional comparisons with other oil-dependent regions are limited, restricting insights into best practices the GCC could adopt to balance economic growth with environmental sustainability. Addressing these gaps is essential for creating comprehensive strategies that promote sustainable development in GCC countries.

3. Materials and Methods

3.1. Data Resource

The data for this study were sourced from the World Development Indicators (WDI), a comprehensive database maintained by the World Bank. The WDI provides annual time-series data covering various economic, social, and environmental indicators for countries worldwide. For this study, key variables such as CO₂ emissions, GDP per capita, electricity consumption, internet users (as a proxy for ICT development), trade openness, and FDI inflows were extracted from the WDI for the six GCC countries (Saudi Arabia, Kuwait, Qatar, Oman, Bahrain, and the United Arab Emirates) over the period from 1990 to 2022. This dataset ensures reliable and consistent data across the countries and time frame, allowing for robust panel data analysis on the factors contributing to environmental degradation in the GCC region.

3.2. Methods

The research methods used in this study, including Fully Modified Ordinary Least Squares (FMOLS) and Autoregressive Distributed Lag (ARDL) models, offer robust long-term estimates and flexibility in handling mixed integration orders. However, FMOLS relies on large sample sizes and cannot fully capture time-varying heterogeneity, while ARDL may face challenges with lag structure specification. These methods are well-suited to analyzing long-term environmental and economic relationships in the GCC context despite their limitations.

3.3. Variables Definition

3.3.1. Dependent Variable

Carbon dioxide emissions, denoted by (CO₂), are one of the most widely used indicators for ED. CO₂ emissions (metric tons per capita) represent the amount of carbon dioxide emitted per capita and reflect the impact of industrial activity, energy consumption, and transportation on the environment. As CO₂ emissions are a standard proxy for environmental degradation, the study uses CO₂ as an indicator of environmental degradation.

3.3.2. Independent Variables

Gross domestic product per capita, denoted by (GDPC), represents the total monetary value of all goods and services produced within a country over a specific period, usually annually. It is commonly used as a measure of a country's economic performance and development. In the context of this study, GDP per capita will be used to capture the average income per person, reflecting the level of economic development in a country.

Energy consumption, denoted by (EC), is the total primary energy consumption, measured in terms of kilowatt-hours (kWh) or million tons of oil equivalent (Mtoe), which refers to the total energy consumed by a country from all sources, including oil, natural gas, coal, nuclear, and renewables. Units of measurement are kilowatt-hours (kWh) or million tons of oil equivalent (Mtoe).

Foreign direct investment, denoted by (FDI), represents net inflows of foreign direct investment, expressed as a percentage of GDP. It refers to investments made by foreign entities into the economy of a host country, typically to establish business operations or acquire assets. FDI can promote economic growth, but may also lead to environmental degradation, especially in resource-intensive industries. FDI is widely used as an indicator of foreign investment flows due to its role in driving economic activity.

Trade openness, denoted by (TO), reflects the extent to which a country engages in international trade, calculated as the sum of exports and imports of goods and services as a percentage of GDP.

Electricity consumption, denoted by (EC), refers to the total amount of electrical energy used by a country or region. This includes electricity used by households, businesses, and industries for lighting, heating, cooling, and operating machinery, appliances, and other electrical equipment. Electricity consumption is often measured in kilowatt-hours (kWh) or gigawatt-hours (GWh).

Information and communication technology development is denoted by (ICT), and in this study, internet users serve as a key indicator of ICT. It refers to the number of individuals in a country or region who have access to and use the Internet, whether through fixed broadband, mobile networks, or other forms of Internet connectivity. The rate of internet penetration is often used as a proxy for the level of digital infrastructure and ICT adoption in a country.

3.4. Descriptive Statistics

Table 1 contains summary statistics for the variables CO₂, EC, FDI, GDP, IU, and TR. The means for CO₂, EC, FDI, GDP, IU, and TR are 22.60, 10,276.46, 2.10, 4.62, 41.14, and 103.16, with standard deviations 9.25, 5450.15, 3.396, 8.80, 39.09, and 31.26, respectively. FDI and GDP are the most skewed and have high kurtosis, indicating that these variables have extreme outliers and are not symmetrically distributed. CO₂, EC, and TR are relatively less skewed and closer to normal distribution than FDI and GDP. All variables failed the normality test (based on the Jarque–Bera statistics), indicating that the dataset does not follow a normal distribution. Furthermore, Table 1 shows high variability in energy consumption, GDP, and trade openness across the dataset, as evidenced by high standard deviations and the sum of squared deviations.

Table 1. Descriptive statistics.

Statistic	CO ₂	EC	FDI	GDP	IU	TR
Mean	22.59505	10,276.46	2.101414	4.619971	41.14101	103.1642
Median	22.07355	10,246.41	1.039541	3.914089	28.55384	93.69325
Maximum	47.65696	21,230.08	29.52007	82.80933	100.0000	191.8726
Minimum	5.840530	1019.063	−4.650769	−41.00779	0.000000	49.71348

Std. Dev.	9.252780	5450.145	3.395376	8.801431	39.09035	31.25532
Skewness	0.667281	0.169286	3.718992	3.095948	0.348356	0.955069
Kurtosis	3.141790	1.910129	25.72839	37.72462	1.471073	3.042147
Jarque–Bera	14.85956	10.74521	4718.203	10264.15	23.28996	30.11581
Probability	0.000593	0.004642	0.000000	0.000000	0.000009	0.000000
Sum	4473.820	2,034,739	416.0799	914.7542	8145.920	20,426.51
Sum Sq. Dev.	16,865.95	5.85E+09	2271.131	15,260.64	301,027.0	192,448.4
Observations	198	198	198	198	198	198

3.5. Model Framework

The model framework of this study seeks to investigate the relationship between various economic factors (such as energy consumption, FDI, trade openness, and internet usage) and environmental degradation (ED) in the GCC countries. The framework will employ a panel data approach, with environmental degradation (measured through CO₂ emissions) as the dependent variable, and the independent variables including electricity consumption (EC), foreign direct investment (FDI), and internet users (as an indicator of ICT development), along with other control variables, such as GDP per capita and trade openness. The model aims to capture how these economic and technological factors contribute to environmental degradation, particularly in the context of the GCC's energy-intensive economies.

Model Specification:

The empirical model used in the study will be based on a multiple regression equation to capture the relationship between environmental degradation and its determinants:

$$Ed_{it} = \beta_0 + \beta_1 EC_{it} + \beta_2 FDI_{it} + \beta_3 IU_{it} + \beta_4 GDPC_{it} + \beta_5 TR_{it} + \epsilon_{it} \quad (1)$$

where:

- Ed_{it} is the environmental degradation (proxied by CO₂ emissions) in country i at time t ;
- EC_{it} is the electricity consumption in country i at time t ;
- FDI_{it} is a foreign direct investment in country i at time t ;
- IU represents ICT development in country i at time t ;
- $GDPC_{it}$ is the GDP per capita in country i at time t ;
- TR_{it} is the trade openness in country i at time t ;
- ϵ_{it} is the error term, capturing unobserved factors affecting environmental degradation in country i at time t .

In this study, the Ordinary Least Squares (OLS) model specification was chosen over other models due to the relatively small variation in time-invariant variables across GCC countries, which limits the advantages of other approaches in this context. In addition, the OLS model provides sufficient explanatory power for the research focus and data structure of this study.

3.6. Econometric Methodology

The econometric methodology employed to assess the long-term relationships between environmental degradation and key economic factors, such as electricity consumption, foreign direct investment, internet usage, trade openness, and GDP per capita, in GCC countries relies on cointegration analysis. Cointegration techniques enable the modeling of long-term equilibrium relationships between non-stationary variables while accommodating short-term deviations. Given the non-stationary nature of macroeconomic time series data, cointegration methods offer a robust approach for capturing the long-run dynamics among these variables.

3.6.1. Panel Data and Stationarity Tests

Before conducting a cointegration analysis, it is essential to verify that the time series data used in the study are non-stationary but integrated in the same order, typically $I(1)$. To confirm this, we use panel augmented Dickey–Fuller (ADF) unit root tests, which assess the presence of unit roots across cross-sectional units (GCC countries) over time. This test determines whether each variable shows non-stationary behavior at the level but becomes stationary after first differencing. Confirming the integration order of the variables is a crucial preliminary step, as it validates the suitability of cointegration methods for examining long-term relationships. If the variables are integrated of different orders, cointegration analysis may not be appropriate, and alternative methodologies would need to be considered.

3.6.2. Cointegration Testing

Once the variables are confirmed as non-stationary and integrated of the same order, the next step is to test for cointegration, which indicates a stable, long-term relationship between the dependent and independent variables despite short-term fluctuations. A widely used panel cointegration test in this context is the Johansen Fisher panel cointegration test, which extends the Johansen cointegration test to panel data, allowing for the assessment of one or more cointegrating relationships among variables. This test examines the rank of the cointegration matrix and provides statistics to determine the number of cointegrating vectors, making it well-suited for analyzing the long-term relationship between environmental degradation and economic factors like GDP per capita, electricity consumption, FDI, and internet usage across GCC countries.

If cointegration is detected, it suggests that while the variables may be non-stationary in the short term, they share a stable, long-run equilibrium relationship. This finding would indicate that environmental degradation in the GCC is influenced by economic variables such as electricity consumption, FDI, and ICT development over time.

3.6.3. Vector Autoregressive (VAR)

The VAR model is a statistical method used in econometrics to analyze the relationships between multiple time series variables. In a VAR model, each variable is treated as endogenous, meaning each is explained by its past values and the past values of other variables in the system. This makes it useful for studying how variables like economic growth, FDI, and energy consumption interact over time. VAR models are flexible, as they do not assume specific dependent or independent variables, and they rely on lag structures to capture historical relationships. Key outputs include impulse response functions and variance decompositions, which show how shocks to one variable affect others in the system. This makes VAR models essential for forecasting and understanding dynamic economic interactions.

3.6.4. Estimating Long-Run Relationships

Once cointegration is established, the study proceeds to estimate the long-term relationship between the variables using appropriate econometric techniques, such as Dynamic Ordinary Least Squares (DOLS). This method is designed to address the issues of endogeneity and serial correlation that often arise in cointegrated systems. DOLS further refines the estimation of long-term relationships by including leads and lags of the first differences of the independent variables. This technique helps capture dynamic interactions between the variables and controls for endogeneity by modeling how past and future changes in the independent variables affect environmental outcomes. The inclusion of these dynamic elements ensures that the estimated coefficients reflect the true long-term effects, even in the presence of short-term fluctuations.

3.6.5. Error Correction Model (ECM)

To complement the long-term analysis, an Error Correction Model (ECM) can be estimated to capture the short-term dynamics and the speed of adjustment toward the long-run equilibrium. The ECM includes a term representing the deviation from the long-run equilibrium (the error correction term), allowing for an analysis of how quickly the system returns to equilibrium after short-term shocks.

The ECM equation takes the following general form:

$$\Delta CO_{2it} = \alpha + \sum \beta_i \Delta X_{it} + \lambda \cdot ECM_{it-1} + \epsilon_{it} \quad (2)$$

where:

- ΔCO_{2it} represents the short-term change in CO₂ emissions;
- ΔX_{it} represents the first differences of the independent variables (e.g., electricity consumption, FDI, internet users, etc.);
- ECM_{it-1} is the lagged error correction term, representing the deviation from the long-run equilibrium; and
- λ is the speed of adjustment parameter, indicating how quickly the system reverts to equilibrium following a short-term disturbance.

The error correction coefficient (λ) is expected to be negative, confirming the presence of a long-run relationship and indicating the percentage of the deviation from equilibrium that is corrected in each period. The ECM not only captures short-term dynamics but also strengthens the evidence of cointegration by demonstrating how the system adjusts to restore equilibrium.

3.6.6. Diagnostic and Robustness Tests

To ensure the validity of the results, several diagnostic tests will be performed, including checks for serial correlation, heteroskedasticity, and multicollinearity.

By utilizing these econometric techniques, the study offers a thorough analysis of the long-term relationship between environmental degradation and its economic drivers in the GCC countries. This approach provides valuable insights into the sustainability of economic policies, assisting policymakers in crafting strategies that balance economic growth with environmental protection.

4. Results

4.1. Augmented Dickey-Fuller Test (ADF)

The ADF unit root tests evaluate stationarity in the time series data of CO₂, EC, FDI, GDP, IU, and TR. In a unit root test, the null hypothesis asserts that the time series possesses a unit root, indicating non-stationarity. Rejection of this hypothesis implies that the series is stationary, either in levels or after differencing. According to Table 2, both FDI and GDP are stationary in levels, while CO₂ and TR are non-stationary in levels but become stationary after first differencing. EC and IU, however, were non-stationary in both levels and first differences, achieving stationarity only at the second difference (integrated of order 2). These findings indicate that some variables, such as FDI and GDP, are stationary in levels, suggesting they revert to a long-term mean and do not exhibit persistent trends. Other variables, such as CO₂ and EC, need to be differenced to remove trends and achieve stationarity. This is important for econometric modeling, as using non-stationary variables in regression analysis can lead to spurious results.

Table 2. ADF unit root test result.

H0	Level					1st Difference					2nd Difference				
	1%	5%	10%	t-Stat	Prob	1%	5%	10%	t-Stat	Prob	1%	5%	10%	t-Stat	Prob

CO ₂	−3.68	−2.97	−2.62	0.02	0.95	−3.68	−2.97	−2.62	−3.53	0.01					
EC	−3.67	−2.96	−2.62	1.76	1.00	−3.67	−2.96	−2.62	−1.77	0.39	−3.67	−2.96	−2.62	−12.58	0.00
FDI	−3.65	−2.96	−2.62	−4.15	0.00										
GDP	−3.65	−2.96	−2.62	−4.64	0.00										
IU	−3.65	−2.96	−2.62	1.61	1.00	−3.67	−2.96	−2.62	−4.04	0.00	−3.67	−2.96	−2.62	−4.19	0.00
TR	−3.65	−2.96	−2.62	−1.35	0.59	−3.67	−2.96	−2.62	−4.19	0.00					

4.2. The Pesaran Cross-Dependence (CD) Test

The Pesaran CD test is a statistical tool used to assess cross-sectional dependence in panel data. Cross-sectional dependence occurs when the residuals or variables across different units (e.g., countries, regions, or firms) are correlated. This issue is common in panel data due to global shocks, unobserved common factors, or spatial interactions, and it can bias estimations and inferences if not addressed. The Pesaran CD test is robust to both balanced and unbalanced panels and does not impose strict assumptions about the underlying data structure. It calculates the average of the pairwise correlations of residuals across cross-sectional units and tests whether this average correlation significantly deviates from zero. A significant result (p -value < 0.05) indicates the presence of cross-sectional dependence. The Pesaran CD test is widely used in econometrics and applied research for ensuring robust analyses of panel datasets.

As shown in Table 3, the low p -value (< 0.05) indicates significant cross-sectional dependence in the panel data. This suggests that the variables in the dataset are correlated across cross-sectional units (e.g., countries).

Table 3. Pesaran CD test result.

	Statistic	p -Value
Pesaran CD Test	3.4864779	0.00049

4.3. Correlation Test

The correlation matrix is used to display the pairwise correlations between different variables, where each value represents the strength and direction of the linear relationship between two variables. The values range from -1 (perfect negative correlation) to $+1$ (perfect positive correlation), with 0 indicating no linear relationship. Based on Table 4, EC is strongly correlated with CO₂ emissions and IU, suggesting that both energy consumption and ICT development play significant roles in environmental outcomes in the GCC region.

Moreover, FDI inflows and GDP have generally weak relationships with environmental and energy variables, though FDI shows some positive correlation with internet users, hinting at its possible role in promoting ICT development. However, TR does not appear to have a strong direct relationship with the other variables, suggesting that trade's environmental and economic impacts may be more indirect or require further analysis to capture complex dynamics.

Table 4. Correlation matrix of the variables.

	LN_CO2	LN_EC	LN_FDI	LN_GDP	LN_IU	LN_TR
Ln CO ₂	1					
Ln EC	0.594	1				
Ln FDI	0.087	0.073	1			
Ln GDP	0.326	0.024	0.196	1		
Ln IU	0.205	0.512	0.163	0.034	1	
Ln TR	0.024	0.299	0.054	−0.058	0.038	1

4.4. Autoregressive Distributed Lag (ARDL) Test

Table 5 presents the long-run ARDL model results, highlighting the relationships between the dependent variable and key independent variables: energy consumption (EC), foreign direct investment (FDI), gross domestic product (GDP), internet users (IU), and trade openness (TR). The coefficients indicate the direction and magnitude of these relationships; for instance, EC, IU, and TR have positive coefficients, suggesting they contribute to increases in the dependent variable, while FDI and GDP show negative coefficients, indicating a mitigating effect. The t-statistics are extraordinarily high due to extremely low standard errors, which may signal computational artifacts or issues such as multicollinearity or model overfitting. Despite these concerns, the *p*-values of 0.0000 for all variables suggest their relationships are statistically significant at conventional levels. The results imply that EC, IU, and TR exert significant positive long-run effects, whereas FDI and GDP reduce the dependent variable. However, the unusually low standard errors necessitate further verification to ensure the robustness of these findings.

Table 5. Long-run ARDL.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
EC	0.000964	1.05×10^{-9}	916,040.0	0.0000
FDI	−1.901674	1.28×10^{-6}	−1,486,570.0	0.0000
GDP	−0.221800	4.15×10^{-7}	−534,776.2	0.0000
IU	0.089065	1.07×10^{-7}	832,819.4	0.0000
TR	0.153961	9.38×10^{-8}	1,641,978.0	0.0000

4.5. Fully Modified Ordinary Least Squares (FMOLS) Test

The FMOLS regression is frequently used to estimate long-run relationships in cointegrated systems. This method corrects for serial correlation and endogeneity in cointegrated panel data, ensuring robust long-term estimates. The results in Table 6 reveal that IU has a significant negative effect on CO₂ emissions (*p*-value = 0.0000), suggesting that increased internet use is associated with a substantial reduction in CO₂ emissions in GCC countries over the long term. Conversely, TR has a significant positive effect on CO₂ emissions (*p*-value = 0.0000), indicating that higher trade openness is linked to a notable increase in CO₂ emissions in the long run. The relationship between EC and CO₂ emissions is positive but only marginally significant (*p*-value = 0.0692), meaning it is not strong enough to be deemed significant at the conventional 5% level. Furthermore, FDI shows a negative coefficient; however, this relationship is not statistically significant (*p*-value = 0.3896), implying that FDI does not have a clear long-term impact on CO₂ emissions in GCC countries within this model. Similarly, GDP has a positive coefficient but is also not statistically significant (*p*-value = 0.1290), aligning with the Environmental Kuznets Curve (EKC) hypothesis, where economic growth eventually leads to reduced environmental harm. These findings, supported by significant t-statistics and *p*-values, provide valuable

insights for policymakers on the drivers of environmental degradation and potential pathways for sustainable development.

Table 6. FMOLS results of EViews 12.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
EC	0.000470	0.000257	1.827647	0.0692
FDI	−0.135846	0.157529	−0.862356	0.3896
GDP	0.075507	0.049518	1.524828	0.1290
IU	−0.109716	0.015111	−7.260601	0.0000
TR	0.212404	0.023723	8.953474	0.0000

4.6. Unrestricted Cointegration Rank Test

The unrestricted cointegration rank test (Trace and Maximum Eigenvalue) assesses the presence of a long-term equilibrium relationship (cointegration) among the variables in the dataset. The results of both the Trace test and the Maximum Eigenvalue test are shown for different hypothesized numbers of cointegrating equations. Both tests provide strong evidence for at least one cointegrating relationship among the variables. According to Table 7, there may be up to five cointegrating equations, indicating a long-term equilibrium relationship between the variables in the system. This suggests that, although the individual variables may be non-stationary, there are stable long-term relationships among them, ensuring they move together over time despite short-term fluctuations.

Table 7. Unrestricted cointegration rank test.

Hypothesized No. of CE(s)	Fisher Stat. (From Trace Test)	Prob.	Fisher Stat. (From Max-Eigen Test)	Prob.
None	156.6	0.0000	96.20	0.0000
At most 1	75.25	0.0000	36.08	0.0003
At most 2	46.19	0.0000	23.53	0.0236
At most 3	30.63	0.0022	15.43	0.2188
At most 4	25.22	0.0138	16.21	0.1820
At most 5	28.63	0.0045	28.63	0.0045

4.7. VAR Test

The VAR lag order selection criteria help determine the optimal number of lags to use in the model for the selected endogenous variables. Table 8 shows the majority of the criteria, such as Final Prediction Error (FPE), Akaike Information Criterion (AIC), Schwarz Information Criterion (SC), and Hannan-Quinn Information Criterion (HQ). The optimal lag length for the VAR model is 1 lag.

Table 8. VAR lag order selection criteria.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	−1291.71	NA **	0.024297	13.30984	13.41055	13.35062
1	−574.0996	1383.699	0.0000 *	6.318971 *	7.023924 *	6.604398 *
2	−552.5133	40.29447	0.0000	6.466803	7.776003	6.996883
3	−522.3523	54.44457 *	0.0000	6.52669	8.440136	7.301421

(*) indicate the optimal lag for the model according to each criterion; (**) Not Available.

4.8. Individual Cross-Section Test

The Trace test evaluates the null hypothesis of no cointegration (or the presence of fewer cointegrating relationships) against the alternative of more cointegrating relationships. A higher Trace statistic indicates stronger evidence of cointegration. However, the

Max-Eigen test examines the null hypothesis of a certain number of cointegrating relationships versus the alternative of an additional cointegrating relationship. A higher Max-Eigen statistic also indicates stronger evidence of cointegration. Based on Table 9, all countries (KSA, Qatar, Kuwait, Oman, Bahrain, and UAE) show evidence of cointegration, as the p -values are below 0.05 for both the Trace and Max-Eigen tests. Furthermore, Kuwait and UAE show the strongest cointegration (as indicated by their very high test statistics and low p -values), suggesting strong long-term equilibrium relationships among their variables. Oman and Bahrain show somewhat weaker evidence of cointegration compared to other countries, but there is still significant evidence of long-term relationships.

The existence of cointegration in these GCC countries indicates that while the individual variables may be non-stationary, there is a long-term equilibrium that ties them together. In economic terms, it means that these countries' economic variables (such as CO₂ emissions, EC, FDI, GDPC, IU, and TR) move together in the long run, even though they might experience short-term fluctuations.

Table 9. Individual cross-section results.

Cross Section	Trace Test Statistics	Prob.	Max-Eigen Test Statistics	Prob.
KSA	153.3940	0.0000	48.4072	0.0046
Qatar	123.2757	0.0002	52.8789	0.0001
Kuwait	158.1502	0.0000	73.2305	0.0000
Oman	130.2283	0.0004	45.6088	0.0129
Bahrain	116.7757	0.0000	45.2477	0.0160
UAE	163.9791	0.0000	74.8525	0.0000

4.9. Dumitrescu-Hurlin Panel Causality Tests

The pairwise Dumitrescu–Hurlin panel causality tests are used to examine the direction of causality between variables in a panel data context. These tests determine if one variable can predict another (Granger causality) while accounting for both time and cross-sectional dependencies. The W -statistic is employed to test the null hypothesis of no causality, while the Z -bar statistic, a normalized version of the W -statistic, is used for inference, providing a clearer basis for interpreting causality relationships. Based on Table 10: EC → CO₂: The p -value is 0.0006, which is statistically significant, meaning EC homogeneously causes CO₂.

FDI → CO₂: The p -value is 0.0206, indicating a significant causality from FDI to CO₂.

GDP → CO₂: The p -value is 0.7975, indicating no causality from GDP to CO₂.

IU → CO₂: The p -value is 0.2067, indicating no significant causality from IU to CO₂.

TR → CO₂: The p -value is 0.4044, indicating no significant causality from TR to CO₂.

TR → CO₂: The p -value is 0.4044, indicating no significant causality from TR to CO₂.

FDI → EC: The p -value is 0.5084, indicating no significant causality from FDI to EC.

EC → FDI: The p -value is 0.0220, indicating significant causality from EC to FDI.

GDP → EC: The p -value is 0.8581, indicating no significant causality from GDP to EC.

EC → GDP: The p -value is 0.1815, indicating no significant causality from EC to GDP.

IU → EC: The p -value is extremely low (0.000), indicating strong causality from IU to EC.

EC → IU: The p -value is 0.0007, indicating significant causality from EC to IU.

TR → EC: The p -value is 0.6047, indicating no significant causality from TR to EC.

EC → TR: The p -value is 0.000, indicating strong causality from EC to TR.

GDP → FDI: The p -value is extremely low (0.000), indicating strong causality from GDP to FDI.

FDI → GDP: The p -value is 0.3770, indicating no significant causality from FDI to GDP.

IU → FDI: The p -value is 0.0246, indicating significant causality from IU to FDI.

FDI → IU: The p -value is 0.0051, indicating significant causality from FDI to IU.
 TR → FDI: The p -value is 0.1978, indicating no significant causality from TR to FDI.
 FDI → TR: The p -value is 0.3155, indicating no significant causality from FDI to TR.
 IU → GDP: The p -value is 0.0385, indicating significant causality from IU to GDP.
 GDP → IU: The p -value is 0.1818, indicating no significant causality from GDP to IU.
 TR → GDP: The p -value is 0.000, indicating strong causality from TR to GDP.
 GDP → TR: The p -value is 0.3338, indicating no significant causality from GDP to TR.
 TR → IU: The p -value is 0.0022, indicating significant causality from TR to IU.
 IU → TR: The p -value is extremely low (0.000), indicating strong causality from IU to TR.

Table 10. Pairwise Dumitrescu–Hurlin panel causality tests.

Null Hypothesis	W-Stat.	Zbar-Stat.	Prob.
EC does not homogeneously cause CO ₂	5.46172	3.42665	0.0006
CO ₂ does not homogeneously cause EC	2.97962	0.84542	0.3979
FDI does not homogeneously cause CO ₂	4.39296	2.31522	0.0206
CO ₂ does not homogeneously cause FDI	1.86	−0.31891	0.7498
GDP does not homogeneously cause CO ₂	2.41338	0.25567	0.7975
CO ₂ does not homogeneously cause GDP	6.73698	4.75285	0.000
IU does not homogeneously cause CO ₂	3.38084	1.26267	0.2067
CO ₂ does not homogeneously cause IU	5.66046	3.63333	0.0003
TR does not homogeneously cause CO ₂	2.96836	0.83372	0.4044
CO ₂ does not homogeneously cause TR	2.32406	0.16368	0.87
FDI does not homogeneously cause EC	1.53078	−0.66129	0.5084
EC does not homogeneously cause FDI	4.36934	2.29065	0.022
GDP does not homogeneously cause EC	1.9948	−0.17873	0.8581
EC does not homogeneously cause GDP	3.4514	1.33604	0.1815
IU does not homogeneously cause EC	7.49028	5.53624	0.000
EC does not homogeneously cause IU	5.41792	3.38111	0.0007
TR does not homogeneously cause EC	2.66438	0.5176	0.6047
EC does not homogeneously cause TR	6.6867	4.70056	0.000
GDP does not homogeneously cause FDI	7.47918	5.52469	0.000
FDI does not homogeneously cause GDP	1.31713	−0.88347	0.377
IU does not homogeneously cause FDI	4.32731	2.24694	0.0246
FDI does not homogeneously cause IU	4.85846	2.7993	0.0051
TR does not homogeneously cause FDI	0.92821	−1.28792	0.1978
FDI does not homogeneously cause TR	3.13183	1.00372	0.3155
IU does not homogeneously cause GDP	4.1562	2.06899	0.0385
GDP does not homogeneously cause IU	0.88023	−1.33782	0.1818
TR does not homogeneously cause GDP	6.22208	4.21738	0.000
GDP does not homogeneously cause TR	3.09596	0.96641	0.3338
TR does not homogeneously cause IU	5.11547	3.06657	0.0022
IU does not homogeneously cause TR	8.45435	6.53881	0.000

In summary, evidence suggests bi-directional causality in certain variable pairs, like $IU \leftrightarrow EC$, $EC \leftrightarrow FDI$, $IU \leftrightarrow FDI$, and $TR \leftrightarrow IU$. In addition, significant one-way causality is observed from EC to CO₂, CO₂ to GDP, CO₂ to IU, GDP to FDI, IU to GDP, and TR to GDP, among others. However, some relationships show no significant causality in either direction, such as $CO_2 \leftrightarrow TR$, $GDP \leftrightarrow EC$, and $FDI \leftrightarrow TR$. This suggests intricate interactions between the variables, with particular importance on the relationships involving CO₂, EC, IU, and GDP

5. Discussion

This research seeks to evaluate the impact of ICT advancement, economic development, trade liberalization, FDI inflows, and electricity usage on environmental degradation in GCC nations during the period from 1990 to 2022. The results of the study demonstrate that the expansion of ICT, measured through the proxy of internet users, has had a multifaceted impact on environmental degradation in GCC countries. The multifaceted impact indicates that ICT growth does not have a straightforward effect. On the one hand, ICT can foster energy-efficient innovations, which could theoretically reduce environmental harm. However, the expansion of internet use also requires substantial digital infrastructure, such as data centers, which consume vast amounts of electricity, often generated from non-renewable resources in the GCC. As a result, the digital transformation associated with ICT growth can lead to increased energy use and higher CO₂ emissions, contributing to environmental degradation.

This contributes to higher electricity consumption, thus exacerbating CO₂ emissions in the region. However, [31] concluded that innovative digital technologies will enhance efficiency and lower carbon emissions. The relationship between ICT development and environmental impact has been echoed in multiple studies, such as the findings by [11,32,33], which highlight the dual role of ICT in both modernizing economies and increasing environmental pressure through its significant energy demands. The environmental costs of ICT development must therefore be managed through sustainable policies that integrate renewable energy sources into the digital infrastructure.

Economic growth, predominantly driven by the oil and gas sectors in the GCC, continues to have a substantial impact on environmental sustainability. The study's findings align with the Environmental Kuznets Curve (EKC) hypothesis, which suggests that environmental degradation initially rises with early economic development, particularly in resource-rich regions like the GCC [34,35]. However, as economies diversify and adopt sustainable technologies, environmental pressures may begin to decline. This conclusion is echoed by [13], who explored the relationship between economic growth and environmental degradation and recommended further investments in sustainable energy to reduce fossil fuel dependency. Additionally, economic diversification strategies, such as those highlighted by [14], suggest that sectors like tourism and renewable energy can offset the environmental costs associated with traditional economic activities.

Trade openness in the GCC has had mixed environmental effects. While expanded trade has driven economic growth by boosting resource-intensive industries, including petrochemicals, manufacturing, and energy production, it has also led to notable environmental degradation through increased CO₂ emissions and resource depletion. This aligns with studies by [36,37]. The pollution haven effect is evident, as industries with high pollution outputs are often drawn to countries with relatively lax environmental regulations, a trend supported by [21], who reported the negative environmental impact of trade liberalization in the GCC. However, studies by [22,38] suggest that trade could contribute positively by facilitating the import of cleaner technologies, emphasizing that trade can play a pivotal role in reducing environmental harm if managed effectively.

Foreign direct investment (FDI) has been crucial in driving industrial growth in the GCC, particularly in the oil, gas, and manufacturing sectors. However, FDI's environmental costs are significant, as increased foreign capital has exacerbated pollution in resource-intensive industries. The study suggests that FDI's environmental impact largely depends on the regulatory environment of the host country. Notably, ref. [39] observed that once education levels in host countries reach certain thresholds, FDI inflows could potentially reduce CO₂ emissions. Similarly, findings by [40] indicate that FDI inflows from certain countries to BRICS nations increased carbon emissions, supporting the pollution haven

hypothesis, whereas FDI from other sources contributed to emission reductions, aligning with the pollution halo effect. Refs. [23,41] also found that, in the absence of stringent environmental regulations, FDI can drive up CO₂ emissions and resource depletion. Nonetheless, FDI also offers opportunities for technology transfer, which could mitigate environmental degradation if policies are in place to promote green investments.

Electricity consumption remains a primary driver of environmental degradation in the GCC, where fossil fuel-based electricity generation contributes significantly to CO₂ emissions. The findings align with [2,42,43], who noted that electricity consumption has consistently exacerbated environmental degradation in the region in both the short and long run. The reliance on non-renewable energy sources continues to present major challenges for sustainability in the GCC. Investments in renewable energy, such as solar and wind power, are urgently needed to reduce the environmental impact of electricity consumption.

This study underscores several important policy implications for the GCC countries. First, stricter environmental regulations are necessary to ensure that economic growth, trade, and FDI do not further contribute to environmental degradation. Policymakers should focus on promoting renewable energy sources and enhancing energy efficiency across industries. Additionally, policies that encourage the transfer of green technologies through trade and FDI could help mitigate the environmental impact of economic activities. These strategies will be critical for balancing economic growth with environmental sustainability in the region.

6. Conclusions

This study aimed to investigate the impact of ICT development, economic growth, trade openness, FDI inflows, and electricity consumption on environmental degradation in GCC countries from 1990 to 2022. The analysis showed that ICT development, reflected by increased internet usage, has had a mixed environmental impact. While digital technologies offer opportunities for efficiency improvements, the energy demands associated with expanding ICT infrastructure have contributed to rising CO₂ emissions. This finding highlights the importance of incorporating renewable energy sources into the ICT sector to mitigate its environmental footprint.

Economic growth, particularly in the oil-dependent economies of the GCC, has followed the EKC pattern. In the early stages of growth, environmental degradation intensified due to the reliance on fossil fuels and energy-intensive industries. However, as these economies mature and begin to diversify into non-oil sectors and adopt cleaner technologies, there is potential for environmental conditions to improve. Nonetheless, the pace of this transition has been slow, and more significant investments in green technologies are required to reverse the environmental harm caused by decades of fossil fuel dependence.

This study also found that trade openness and FDI inflows have contributed to both economic growth and environmental challenges in the GCC. Trade openness has enabled the expansion of resource-heavy industries such as petrochemicals, leading to increased CO₂ emissions and resource depletion. Similarly, FDI inflows, particularly into energy and industrial sectors, have exacerbated pollution levels. This supports the pollution haven hypothesis, where weaker environmental regulations attract pollution-intensive industries. However, the potential for trade and FDI to introduce cleaner technologies and sustainable practices remains largely untapped in the region.

Finally, electricity consumption was identified as a major driver of environmental degradation in the GCC, where fossil fuels dominate electricity generation. The reliance on non-renewable energy sources for electricity not only contributes significantly to CO₂ emissions but also poses long-term sustainability challenges. To address these issues, policymakers must prioritize renewable energy investments, enforce stricter environmental

regulations, and encourage green technology adoption. These steps are crucial for balancing economic development with environmental sustainability, ensuring that the region's growth does not come at the expense of its environmental future.

7. Policy Recommendations

Based on the findings of this study, several key policy recommendations are essential for promoting environmental sustainability while maintaining economic growth in the GCC countries. First, policymakers must accelerate investments in renewable energy sources, such as solar and wind power, to reduce the region's heavy reliance on fossil fuels, which is a primary driver of CO₂ emissions. Stricter environmental regulations should be enforced, particularly targeting resource-intensive sectors like petrochemicals and manufacturing, to mitigate the environmental impact of both trade and FDI inflows. Additionally, trade and FDI should be strategically leveraged to facilitate the transfer and adoption of green technologies and cleaner production methods, helping to modernize industries while minimizing their carbon footprint. Energy efficiency programs must be prioritized, especially within the rapidly growing ICT infrastructure, to curb the rising electricity consumption that contributes to environmental degradation. Finally, comprehensive policies that encourage sustainability and environmental responsibility across all sectors are critical for balancing the region's economic ambitions with long-term environmental protection.

8. Future Research Directions and Limitations

Future research on the relationship between economic growth and environmental degradation in the GCC should focus on several key areas. Studies should examine the long-term effects of transitioning to renewable energy on both the economy and the environment, given the region's potential for clean energy. Research should also assess the effectiveness of environmental policies in reducing the impact of FDI and trade on degradation, identifying gaps for improvement. Comparative studies with other oil-dependent economies could provide insights into balancing growth and sustainability. Additionally, future work should consider other environmental factors like water use and waste management, while exploring how technological innovations, such as smart technologies and AI, can reduce emissions and improve energy efficiency. Recent research, for example [44,45], highlights the substantial environmental impact of transportation emissions and land-use changes, emphasizing the need for sustainable urban planning and transportation policies. Addressing these additional dimensions will provide a more comprehensive understanding of the environmental challenges in the GCC.

This study has limitations, including reliance on historical data from 1990 to 2022, which may not capture recent policy or technological changes. It focuses mainly on CO₂ emissions, overlooking other environmental issues like water scarcity and air quality. The analysis also assumes uniform impacts across GCC countries, ignoring country-specific factors, and does not address potential endogeneity between economic growth and environmental degradation. Future research should include diverse environmental indicators, address endogeneity, and focus on country-specific analyses for more nuanced insights.

In addition, the study does not account for other significant drivers of CO₂ emissions, such as transportation, land-use changes, and urban sprawl, which are critical in the GCC context due to the region's rapid urbanization and reliance on car-centric transportation systems. Future studies should investigate the roles of these factors in contributing to CO₂ emissions and environmental degradation.

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