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Article

Environmental Degradation in GCC: Role of ICT Development, Trade, FDI, and Energy Use

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Abstract: This research examines how Information and Communication Technology (ICT) development, economic growth, trade openness, Foreign Direct Investment (FDI) inflows, and electricity consumption influence 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

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.

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.

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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].

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, [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, [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 addresses the significant issue of sediment displacement in the Gulf of Oman and its effects on coastal ecosystems. The research demonstrates that climate change, alongside infrastructure development, disrupts natural sedimentation processes essential for ecosystem health in the region.

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.

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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 significant factor contributing to environmental concerns in the GCC's ICT sector is the substantial energy consumption needed to operate extensive networks and data centers. [7] examines the connection between technological advancement, economic growth, and CO2 emissions in the GCC, with a focus on the period from 2000 to 2022.The study concludes that the rise in ICT infrastructure, coupled with urbanization and economic development, has contributed significantly to increased CO2 emissions. [7] findings emphasize that while ICT plays a pivotal role in modernizing GCC economies, it comes at an environmental cost due to its dependence on energy-intensive systems, most of which rely on non-renewable energy sources. Moreover [8], address the broader environmental consequences of ICT development, particularly concerning sustainable urban planning and resource management. Their research highlights the potential for ICT to either mitigate or exacerbate environmental degradation depending on how it is implemented. For instance, while ICT can drive efficiency in resource use and reduce energy waste through smart technologies, the lack of sustainable practices in data management and electronic waste disposal can lead to significant environmental harm.

Another critical environmental concern associated with ICT development in the GCC is electronic waste (e-waste). The region's swift adoption of digital devices and infrastructure has increased e-waste production, posing significant challenges for waste management systems that often lack the capacity to handle ICT product disposal and recycling effectively. [8] argue that, without comprehensive e-waste management policies, the environmental impact of ICT will continue to escalate, underscoring the need for sustainable practices across the ICT lifecycle, from production to disposal. While the environmental impact of ICT is evident, both studies propose potential solutions to reduce its ecological footprint. [7] recommends incorporating renewable energy sources into ICT infrastructure, particularly within data centers and telecommunications networks, to reduce CO2 emissions. [8] advocate for the development of green ICT policies that emphasize energy efficiency, sustainable resource use, and enhanced 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 has largely been fuelled by hydrocarbon extraction and export, leading to high carbon emissions and environmental degradation. [9] investigated the EKC hypothesis, which posits that environmental degradation initially rises with economic growth but eventually declines as economies mature and implement cleaner technologies. Their study, which also considered the roles of tourism and ecological footprint, found that despite their economic

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wealth, GCC countries continue to experience substantial environmental stress due to their dependence on fossil fuels. This highlights the need for the GCC to diversify its energy portfolio and adopt more sustainable practices.

The importance of economic diversification for sustainability in the GCC cannot be overstated. [10] from the International Monetary Fund (IMF) highlighted the region's efforts to move away from its dependency on oil and gas. Their report outlines the historical over-reliance on hydrocarbons and emphasizes that diversification into sectors like tourism, finance, and renewable energy is critical for both economic stability and environmental sustainability. The authors argue that while progress has been made, further efforts are required to implement policies that support greener sectors and reduce carbon emissions associated with traditional industries.

A crucial element of the GCC's strategy for balancing economic growth with environmental sustainability lies in developing renewable energy projects. [11] provided a detailed case study on Masdar City, Abu Dhabi's carbon-neutral initiative, as an innovative example of renewable energy policy in the Gulf. This study emphasizes the importance of investments in solar energy and sustainable urban planning in reducing the region's carbon footprint. However [11], 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. [12] analyzed the causal relationships between economic growth, renewable energy use, CO_2 emissions, and trade openness in BRICS countries, offering insights applicable to the GCC. 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. [13] examined the energy-GDP relationship in the GCC using panel data to assess causality. 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 (SO_2) and carbon dioxide (CO_2) emissions in non-OECD countries, despite contributing to a reduction in biochemical oxygen demand (BOD) emissions within these regions [14,17].

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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, [18] 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.

Despite these adverse environmental impacts, trade openness also presents opportunities for cleaner technology transfer. [19] suggest that trade can encourage the adoption of eco-friendly technologies and more efficient production processes, particularly in energy-intensive sectors. 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. [20] 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. [21] advocate 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 fuelled 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. [22] found that FDI inflows in developing economies, including the GCC, tend to correlate with higher carbon emissions and resource consumption due to increased industrial activity. 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 [23,24] 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.

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On a positive note, FDI can facilitate the transfer of environmentally friendly technologies, which helps to reduce the environmental impact of industrial activities. [19] 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 extent to which FDI contributes to environmental degradation depends largely on the host country's regulatory framework. Countries with robust environmental laws are better equipped to ensure that FDI aligns with sustainability goals. In the GCC, however, environmental regulations have traditionally been secondary to economic objectives. Strengthening these regulations, particularly concerning emissions standards and resource management, will be critical in ensuring that FDI does not lead to further environmental degradation. Additionally, implementing environmental impact assessments (EIA) for large FDI projects could help minimize the environmental risks associated with foreign investments.

Thus, while FDI has been a significant driver of economic growth in the GCC, it has also contributed to environmental degradation, especially in resource-intensive sectors like oil and gas. The pollution haven hypothesis underscores the risks associated with attracting foreign investments without robust environmental regulations, as this can lead to heightened pollution and resource depletion. However, FDI also offers opportunities for green technology transfer and environmental enhancements, provided that host countries implement strong regulatory frameworks to direct foreign investments toward 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 CO_2 emissions. [2] analyzed the impact of energy consumption on the environmental footprint of the GCC nations from 2000 to 2019, 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. [25] examined air pollution trends in Dubai, 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. [26] 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. [27] explored the implications of population growth, rising energy demand, and sustainability in the GCC, especially in the context of global climate change efforts. The study suggests 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 is 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. Variables Definition

Dependent Variable:

Carbon Dioxide Emissions: denoted by (CO2), are one of the most widely used indicators for ED. CO2 Emissions (metric tons per capita) is the amount of carbon dioxide emitted per capita and reflects the impact of industrial activity, energy consumption, and transportation on the environment. The study uses CO2 as an indicator of environmental degradation.

Independent Variables:

Gross Domestic Product Per capita: denotes by (GDPC), 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: denotes 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: denotes by (FDI), 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.

Trade Openness: denotes by (TO), it 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.

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Electricity Consumption: denotes 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, 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: denotes by (ICT), 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.

3.3. 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 independent variables including electricity consumption (EC), Foreign Direct Investment (FDI), internet users (as an indicator of ICT development), and 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:

$$Edit = \beta0 + \beta1ECit + \beta2FDIit + \beta3IUit + \beta4GDPCit + \beta5TRit + \epsilon_{it} \quad (1)$$

Where:

- Edit: is the environmental degradation (proxied by CO2 emissions) in country i at time t.
- ECit: is electricity consumption in country i at time t.
- FDIit: is a foreign direct investment in country i at time t.
- Internet Usersit: represents ICT development in country i at time t.
- GDPCit is the GDP per capita in country i at time t.
- TRit: is trade openness in country i at time t.
- ϵit is the error term capturing unobserved factors affecting environmental degradation in country i at time t.

3.4. 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.

3.4.1. 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

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different orders, cointegration analysis may not be appropriate, and alternative methodologies would need to be considered.

3.4.2. 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.

3.4.3. 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.

3.4.4. 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.

3.4.6. 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:

$$\Delta CO2it = \alpha + \sum \beta i \Delta Xit + \lambda \cdot ECMit - 1 + \epsilon it \qquad (2)$$

Where:

- ΔCO2it represents the short-term change in CO2 emissions.

- ΔXit represents the first differences of the independent variables (e.g., electricity consumption, FDI, internet users, etc.).

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-ECMit−1 is the lagged error correction term, representing the deviation from the long-run equilibrium.

-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.

3.4.7. 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

Descriptive Statistics

Table 1. contains summary statistics for the variables CO2, EC, FDI, GDP, IU, and TR. The mean for CO2, EC, FDI, GDP, IU, and TR are (22.60, 10276.46, 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 fail 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 sum of squared deviations.

Table 1. Descriptive Statistics .

Statistic	CO2	EC	FDI	GDP	IU	TR
Mean	22.59505	10276.46	2.101414	4.619971	41.14101	103.1642
Median	22.07355	10246.41	1.039541	3.914089	28.55384	93.69325
Maximum	47.65696	21230.08	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	2034739	416.0799	914.7542	8145.920	20426.51
Sum Sq. Dev.	16865.95	5.85E+09	2271.131	15260.64	301027.0	192448.4
Observations	198	198	198	198	198	198

Augmented Dickey-Fuller Test (ADF)

The ADF unit root tests evaluate stationarity in the time series data of CO_2, 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

CO_2 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**
CO2	-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					

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 3, 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 3. Correlation Matrix of the Variables.

	LN_CO2	**LN_EC**	**LN_FDI**	**LN_GDP**	**LN_IU**	**LN_TR**
Ln CO2	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

Autoregressive Distributed Lag (ARDL) Test.

ARDL model helps estimate the long-term relationship between a dependent variable and several independent variables. Based on Table 4, all variables (EC, FDI, GDP, IU, and TR) have highly significant effects on the dependent variable in the long run, as all p-values are (0.0000), which is far below the 0.05 threshold. Moreover, EC, IU, and TR all have positive coefficients, suggesting that

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increases in these variables affect positively to CO2 in the long term. Conversely, FDI and GDP have negative coefficients, implying that increases in these variables are associated with reductions in the CO2 in the long run. However, the very small standard errors and large t-statistics across all variables imply that the model provides very precise and significant estimates of the long-term relationships.

Table 4. Long Run ARDL.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
EC	0.000964	1.05E-09	916040.0	0.0000
FDI	-1.901674	1.28E-06	-1486570.0	0.0000
GDP	-0.221800	4.15E-07	-534776.2	0.0000
IU	0.089065	1.07E-07	832819.4	0.0000
TR	0.153961	9.38E-08	1641978.0	0.0000

Fully Modified Ordinary Least Squares (FMOLS) Test

The FMOLS regression is frequently used to estimate long-run relationships in cointegrated systems. The results in Table 5 reveal that IU has a significant negative effect on CO_2 emissions (p-value = 0.0000), suggesting that increased internet use is associated with a substantial reduction in CO_2 emissions in GCC countries over the long term. Conversely, TR has a significant positive effect on CO_2 emissions (p-value = 0.0000), indicating that higher trade openness is linked to a notable increase in CO_2 emissions in the long run. The relationship between EC and CO_2 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 CO_2 emissions in GCC countries within this model. Similarly, GDP has a positive coefficient but is also not statistically significant (p-value = 0.1290), indicating no substantial long-term effect of GDP on the dependent variable in this analysis.

Table 5. 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

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 6, there may be up to 5 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 6. 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

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 7. 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 7. 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	2.24e-05*	6.318971*	7.023924*	6.604398*
2	-552.5133	40.29447	2.60E-05	6.466803	7.776003	6.996883
3	-522.3523	54.44457*	2.76E-05	6.52669	8.440136	7.301421

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 8, 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 8. Individual cross-section results.

Cross Section	Trace Test Statistics	Prob.	Max-Eign 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

Dumitrescu- Hurlin panel causality tests

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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 9:

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.

FDI ↔ EC

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

FDI ↔ EC

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

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:

IU → EC: The p-value is extremely low (3.E-08), indicating strong causality from IU to EC.

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

TR ↔ EC:

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

EC → TR: The p-value is 3.E-06, indicating strong causality from EC to TR.

GDP ↔ FDI:

GDP → FDI: The p-value is extremely low (3.E-08), 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:

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:

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:

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:

TR → GDP: The p-value is 2.E-05, 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:

TR → IU: The p-value is 0.0022, indicating significant causality from TR to IU.

IU → TR: The p-value is extremely low (6.E-21), indicating strong causality from IU to TR.

In summary, evidence suggests bi-directional causality in certain variable pairs, like IU ↔ EC, EC ↔ FDI, IU ↔ FDI, and TR ↔ IU. In addition to, 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 CO2 ↔ TR, GDP ↔ EC, and FDI ↔ TR. This suggests intricate interactions between the variables, with particular importance on the relationships involving CO2, EC, IU, and GDP.

Table 9. Pairwise Dumitrescu- Hurlin panel causality tests.

Null Hypothesis	W-Stat.	Zbar-Stat.	Prob.
EC does not homogeneously cause CO2	5.46172	3.42665	0.0006
CO2 does not homogeneously cause EC	2.97962	0.84542	0.3979
FDI does not homogeneously cause CO2	4.39296	2.31522	0.0206
CO2 does not homogeneously cause FDI	1.86000	-0.31891	0.7498
GDP does not homogeneously cause CO2	2.41338	0.25567	0.7975
CO2 does not homogeneously cause GDP	6.73698	4.75285	2.E-06
IU does not homogeneously cause CO2	3.38084	1.26267	0.2067
CO2 does not homogeneously cause IU	5.66046	3.63333	0.0003
TR does not homogeneously cause CO2	2.96836	0.83372	0.4044
CO2 does not homogeneously cause TR	2.32406	0.16368	0.8700
FDI does not homogeneously cause EC	1.53078	-0.66129	0.5084
EC does not homogeneously cause FDI	4.36934	2.29065	0.0220
GDP does not homogeneously cause EC	1.99480	-0.17873	0.8581
EC does not homogeneously cause GDP	3.45140	1.33604	0.1815
IU does not homogeneously cause EC	7.49028	5.53624	3.E-08
EC does not homogeneously cause IU	5.41792	3.38111	0.0007
TR does not homogeneously cause EC	2.66438	0.51760	0.6047
EC does not homogeneously cause TR	6.68670	4.70056	3.E-06
GDP does not homogeneously cause FDI	7.47918	5.52469	3.E-08
FDI does not homogeneously cause GDP	1.31713	-0.88347	0.3770
IU does not homogeneously cause FDI	4.32731	2.24694	0.0246
FDI does not homogeneously cause IU	4.85846	2.79930	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	4.15620	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	2.E-05
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	6.E-21

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, [28,29] 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 [7]; [30]; [31], 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.

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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 [32,33]. However, as economies diversify and adopt sustainable technologies, environmental pressures may begin to decline. This conclusion is echoed by [9], 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 [10]—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 CO_2 emissions and resource depletion. This aligns with studies by [34,36]. 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 [18], who reported the negative environmental impact of trade liberalization in the GCC. However, studies by [19] and [37] 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 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, [38] observed that once education levels in host countries reach certain thresholds, FDI inflows could potentially reduce CO_2 emissions. Similarly, findings by [39] 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**. [40] and [20] also found that, in the absence of stringent environmental regulations, FDI can drive up CO_2 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]; [41,43] 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.

The 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 CO_2 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.

The 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.

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.

7. Future Research Directions & 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.

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

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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.

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