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Evaluating the Impact of Energy Mix and Digital Economy on Ecological Footprint in GCC: Fresh Insight from Panel ARDL Approach

Issa Ahmed AL Balushi[1]*, Nora Yusma Binti Mohamed Yusoff[2]

[1]UNITEN–Putrajaya Campus, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia; abuahmed1145@gmail.com (I.A.A.B.)
[2]Institute of Energy Policy & Research, Universiti Tenaga Nasional UNITEN–Putrajaya Campus, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia; nora@uniten.edu.my (N.Y.B.M.Y.).

Abstract. This study examines the impact of economic growth, digitalization, and energy mix on the ecological footprint in the GCC region from 2000 to 2021. Using advanced econometric techniques, including Panel ARDL, AMG, and CCEMG estimations, the research explores both short-run and long-run dynamics while ensuring robust and valid results. Pre-estimation tests, such as Cross-Sectional Dependence (CSD) and panel unit root tests, confirm that variables are free from unit root problems but exhibit CSD, emphasizing economic interdependencies in the region. Panel cointegration tests reveal long-term equilibrium relationships among the variables. The findings indicate that economic growth, non-renewable energy consumption, and population significantly increase the ecological footprint, highlighting their role in driving environmental degradation. Conversely, renewable energy and digitalization significantly reduce the ecological footprint, showcasing their potential to support environmental sustainability. Validation through AMG and CCEMG methods confirms the robustness of the Panel ARDL results. This study contributes to the understanding of how economic and energy transitions interact with ecological outcomes in resource-rich economies. The results underline the critical need for policies promoting renewable energy, sustainable urbanization, and the integration of digital technologies to balance economic growth with environmental sustainability in the GCC region.

Keywords: Digital Economy, Ecological Footprint, Energy Mix, GCC, Panel ARDL.

1. INTRODUCTION

The explosive increase of global ecological footprint is one of the main sources of environmental vulnerability, and is exacerbated by increasing carbon emissions, unsustainable resource use, and over-urbanisation (Chen et al.2023). Across the planet, the carbon dioxide levels have risen from 280 parts per million (ppm) pre-industrial levels to more than 420 ppm in 2023, which translates to an average temperature increase of around 1.1°C since the late 19th century (Wang et al.2023). More than 35 billion tons of CO2 are released into the atmosphere every year around the world, driving deforestation, biodiversity destruction and rising ecological imbalances (Wang and Cao, 2024). The GCC (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the UAE) has one of the largest ecological footprints per head in the world, and an escalating reliance on fossil fuels and resource-rich ways of life. Qatar's per capita environmental footprint, for example, stands at around 10.5 global hectares (gha) and that of the UAE at 8.9 gha, far higher than the average across the world at 2.8 gha (GFN, 2021). Because the GCC produces 4.5% of the total CO2 emissions and 0.6% of the global population, it has disproportional effects on the environment. Oil and gas exports dominate these economies, and Saudi Arabia produces more than 600 million metric tons of CO2 annually, mostly from energy use (Amoatey et al.2020; Kahouli and Chaaben, 2022). These studies are driven by the need to solve the environmental crisis in the GCC, where increasing urbanisation, water desalination needs and unsustainable consumption patterns worsen the situation. The study seeks to analyse the underlying causes of this expanding ecological footprint such as economic dependence on fossil fuels, energy waste, and the effects of population growth, which has increased by an average of 2.1% per year in the GCC over the last 20 years. The results will offer tangible recommendations on policy reform, sustainable resource use, and renewable energy use to help limit ecological damage. In determining key drivers of ecological overshoot, the study hopes to support local efforts to achieve economic and environmental sustainability in the GCC.

In addition, the ecological footprint of the GCC depends heavily on its energy mix, which is still largely made up of non-renewable resources, such as oil and gas. More than 90% of GCC energy comes from fossil fuels, and Saudi Arabia alone produces more than 10.5 million barrels of oil per day, making it one of the world's largest oil exporters (Nassar, 2024). Renewable energy contributions are, on the other hand, negligible, even given the region's huge potential for solar and wind energy. Renewable energy now accounts for less than 2 per cent of the GCC's overall energy mix, while the UAE is leading the way with initiatives such as the Mohammed bin Rashid Al Maktoum Solar Park which will generate 5,000 MW by 2030 (Ulussever et al.2024). Qatar's is even lower, at under 0.5 per cent, and Oman and Kuwait are trailing behind with very little in the way of renewable energy. Such fossil fuel use also increases per capita CO2 emissions at a rate of 24.6 metric tons across the GCC — more than three times higher than the average global CO2 emission of 7.4 metric tons — thereby putting more pressure on the environment (Alsabbagh, 2024). The energy-hungry methods of desalination and industrial manufacture further compound environmental stresses. In addition to the energy mix, population growth in the GCC contributed to the increasing ecological footprint. Over the last 20 years, the GCC population has risen at an average annual growth rate of 2.1% to approximately 61 million people in 2023. Such countries as Qatar and the UAE, where expatriates are the dominant population (88% and 89% respectively), have seen increased

* Correspondence: abuahmed1145@gmail.com

urbanisation and rising consumption (Ahmed et al.2024). Such population growth has created an additional energy burden, with the average household electricity consumption in the GCC reaching more than 10,000 kWh per year, or twice the global average. Collectively, the unsustainable energy system and a population explosion have left the region in ecological depletion, with resource requirements exceeding natural supply (Alajmi, 2024). Solving these challenges will require a shift to renewables, energy efficiency and population-based sustainability policies to stem the region's increasing ecological footprint.

GCC's digital economy is rapidly burgeoning and is already putting significant pressure on the environment due to its energy-intensive infrastructure and high demand for ICT products and services. As of 2023, GCC nations have spent more than $15 billion on ICT infrastructure, with $6.4 billion financed solely by Saudi Arabia through programmes such as Vision 2030 (Mohammed and Abdel-Gadir, 2023). The UAE and Qatar have the highest ICT adoption, with internet penetration of 99% and 98% respectively, and mobile phone subscriptions reaching more than 150% of the population (Islam et al.2023). This expansion has brought with it an increase in the imports of ICT goods, with the GCC purchasing more than $18 billion worth of ICT hardware every year such as data centres, network hardware and consumer electronics which consumes resources and generates waste (Brahmia and Mannai, 2024). Data centres, a central building block of the digital economy, need enormous amounts of energy; a mid-size data center consumes 20-50MW annually, which is enough to power 15,000 homes, and GCC data centres are powered mostly by fossil fuels (Albreem et al.2023). The ecological impact of the digital economy is also felt in rising electricity use: ICT activities consume an estimated 7% of all electricity usage in the GCC and this figure will increase by 4% annually as cloud computing and AI services become increasingly prevalent. Furthermore, e-waste production in the GCC exceeds 800,000 metric tons per year, with poor recycling facilities compounding environmental impacts (Islam and Rahaman, 2023). Digital transformation benefits diversification and efficiency, but it is not possible to ignore the environmental repercussions of digital transformation, including the energy requirements and waste generation. Since the GCC seeks to be a digital powerhouse for the world, it is crucial that its digital economy takes into account the environment with respect to sustainable ICT, renewable energy in data centres, and policies for e-waste management that meet both development and environmental commitments.

The main goal of this work is to study how economic development, digitalisation, energy mix and population impacts the GCC region's ecological footprint between 2000–2021, at the short- and long-run time scale, using sophisticated econometric models, such as Panel ARDL, AMG and CCEMG estimations. Its goal is to confirm the validity of the results and to provide a robust view of the ways in which renewable energy and digitalisation play a role in reducing ecological burdens, while economic development, non-renewable energy use and population serve as key drivers of degrading the environment. One of its strengths is that it looks at the GCC region – which has one of the largest per-capita ecological footprints in the world, and an intensive dependence on fossil fuels – as a prime candidate for research on sustainable development. By putting economic, technological, energy and demographics into one holistic analysis, it fills a fundamental gap in our understanding of environmental sustainability in resource-intensive economies. Additionally, a strong methodological approach ensures reliability and accuracy of findings and delivers subtle contributions to the literature and will open up the possibilities for further research on how to be sustainable in similarly socioeconomic environments.

2. LITERATURE REVIEW

Economic growth and the ecological footprint are well-documented, with complexities that are different across countries and contexts. Zhang et al. (2024) noted that the per-capita GDP and ecological footprint were positively correlated in 131 countries between 2009 and 2019, highlighting the environmental costs of growth and the need to balance growth with sustainability. Similarly, Ursavas et al. (2024) discovered that India's economic growth between 1973 and 2018 only contributed to further deforestation, which demanded clean energy and greater efficiency. Nguyen et al. (2024) tested the EKC hypothesis in Vietnam and found that economic growth first increases ecological footprint but gradually reduces as income rises, which indicates that it can be sustained by policies. Alsaggaf (2024) found that economic development exacerbated long-term ecological impacts in Gulf Cooperation Council (GCC) nations, emphasising the need for measures to reduce environmental damage while promoting economic development. In Türkiye, Boluk and Kármán (2024) affirmed the EKC hypothesis: economic growth leads first to ecological degradation, and then to ecological improvements as GDP increases. Lian (2024) compared E7 and G7 economies between 2010 and 2022, determining that developed G7 economies successfully cut their ecological footprints through efficiency and public awareness, while E7 countries suffered from developmental and technological inequalities. Ullah et al. (2023) also verified the EKC hypothesis in Turkey, showing that growth adds to ecological footprints both in the short and long run before eventually improving. Last but not least, Aslam (2023) looked at the role of financial development in middle- and high-income economies, and discovered a U-shaped relationship in which higher-level financial systems, such as those in China, created ecological stability. Taken together, these findings highlight the twin issues of how to maximise economic activity without damaging the environment, and they call for specific solutions that draw on technological innovation, policy-making and public education to ensure sustainable development in the world.

Energy mix and environmental footprint are very well studied and show subtle interaction between them in different situations. Bucak et al. (2024) outlined how the use of renewable energy in EU countries not only mitigates local environmental impacts but also produces beneficial spillovers in neighbouring states, while fossil energy use causes further ecological damage. Similarly, Rehman et al. (2021) concluded that both renewable and non-renewable energy use in Pakistan significantly elevated the carbon footprint in the long term, making sustainable energy practices a must-do priority. Nathaniel (2021) pointed to a similar trend in Indonesia, where energy consumption, regardless of the source, caused environmental imbalances, indicating the importance of policies incorporating environmental sustainability into energy consumption. Agbede et al. (2021) confirmed these conclusions in MINT countries, where even a small rise in primary energy use was associated with severe degradation of the environment. In contrast, Nan et al. (2022) found that consuming renewable energy was significantly beneficial in China, with 1 % of renewable energy reducing the ecological footprint by 2.91% (reiterating its importance as an environmental mitigation measure). Majeed et al. (2021) drew a different dimension by analysing asymmetric impacts of energy use in Pakistan and found that negative shocks to energy consumption boosted environmental quality, while positive shocks (notably oil consumption) exacerbated footprints. Akpanke et al. (2024) extended this debate to the OECD and found that renewable energy did reduce environmental impacts in significant ways, whereas non-renewable energy had a less dramatic effect on degraded environments than predicted. Together, these studies highlight the intricate connection between energy use and health, highlighting renewable energy's central role in minimising our ecological footprints.

The intersection of digital economy and environmental footprint has been a rapidly emerging field of study, with heterogeneous findings in various contexts. Dai et al. (2023) demonstrated that the digital economy helped to decrease environmental footprints in developing nations from 2003 to 2018 by allowing more efficient use of resources and clean energy due to digital transformation. Similarly, Kahouli (2022) observed that information and communication technology (ICT) developments in Saudi Arabia reduced ecological impacts, pointing to its potential to enhance resource efficacy and reduce environmental degradation. Khan and Ximei (2022), on the other hand, found inconsistent results across G7 economies from 2001 to 2018: ICT exports raised environmental footprints because they were increasingly requiring the environment, but ICT imports reduced them by decreasing their use of nonrenewable energy, suggesting that the trade element of ICT has significant effects on its environmental footprint. Onwe et al. (2024b) also highlighted the asymmetry of ICT impacts in G7 countries between 1990 and 2020, observing that ICT's ecological effects varied depending on the type of proxy (fixed telephone plans, internet access, etc) and econometric approaches. Zhao et al. (2024) made things even trickier by demonstrating that, although the digital economy can be cleaner in energy terms, it leaves an environmental footprint that is largely undone by the ever-expanding energy needs of digital infrastructures and does not allow renewable energy to make up for its ecological losses. In aggregate, all these results indicate that, although the digital economy has enormous potential to decrease environmental impacts by becoming more efficient and producing cleaner energy transitions, its contribution depends on the underlying context of trade, technological infrastructure and energy policy.

Population growth and ecological footprint has been studied extensively, showing knotty connections between population density and sustainability. Udemba et al. (2024) showed that population growth, and particularly urbanisation driven by rural-urban migration in Russia, increased the ecological footprint considerably, emphasizing the impact of working-age and older populations on natural resources. Similarly, Dasgupta et al. (2023) raised the question of how to maintain an ever-growing population on a planet where the current population rate is already creating ecological footprints that exceed the biosphere's regenerative potential, leaving it with an inexorable loss of natural capital. This world phenomenon speaks to unsustainable population growth. In contrast, Xiao et al. (2018) offered an example in the Taihang Mountains in China, where a 9.7% population decline between 2000 and 2016 was matched by a 32.1% reduction in ecological footprint, demonstrating how a declining population can relieve pressure on the local environment. Anser et al. (2020) provided an elegant answer: it traced an inverted U-shaped relationship between population growth and ecological footprint in 130 countries, where incoming population density created environmental stressors, but economic growth eventually led to the promotion of practices that minimised the footprint. Hanna and Osborne-Lee (2012) used a GEM to demonstrate that increasing population around the world increases energy consumption and carbon footprints at a pace often outstripping the Earth's biological capabilities and creating an opportunity for resource use beyond sustainable levels.

Though the factors that influence environmental sustainability have been well studied, a considerable literature gap exists in the relationship between economic development, digitalisation, energy mix and ecological outcomes in resource-constrained areas like the GCC. Previous analyses tended to isolate individual variables such as energy use or economic development without considering how digitalisation and the energy mix interact to have an impact on environmental sustainability. Further, relatively little has been devoted to analyzing both the short- and long-term changes using modern econometric methods that consider cross-sectional dependence and regional economic interdependencies. Existing research recognises the environmental value of renewable and non-renewable energy, but it often does not reliably confirm results across a variety of econometric approaches, putting policy conclusions at risk. Furthermore, the role of digital technologies as a mitigation agent against ecological collapse has been little explored in the GCC, even as it plays an increasingly prominent role in sustainability policies worldwide. This research fills these discrepancies by adopting a holistic methodological approach, and focusing on how economic development, energy transitions and digitalisation impact the ecological footprint in parallel, while offering a detailed insight tailored to the peculiar dynamics of resource-rich economies.

3. METHODOLOGY

3.1. Data and Variables

The paper analyzes the correlation between EFP and major economic, digital, energy and demographic indicators for GCC countries for 2000–2021. This dependent variable, EFP, which is the ecological footprint per head (global hectares), is logarithmic (LEFP) for proportional impacts, and is derived from the Global Footprint Network (GFN). Uncoupled factors are selected based on their connections to sustainability and economic change. GDP (GDP) — which captures economic output in real US dollars (LGDP) — is one way of describing the ecological effects of economic development, and comes from the World Development Indicators (WDI). Digital Economy (DGE), defined as the percentage of ICT products in total imports (LDGE) calculated by the International Monetary Fund (IMF), reflects the impact of digitalization on resource efficiency. Renewable Energy (REN) and Non-renewable Energy (NRE), which represent as a percentage of total energy consumption (LREN and LNRE), measure how energy composition affects ecological pressure, are derived from the WDI. Population (POP), defined as total population (LPOP), reflects demographic pressures on the ecosystem and comes from the WDI, too. Log-transforming variables standardise units and make proportional impact calculations possible, allowing us to rigorously investigate how they contribute to ecological sustainability in the GCC over the past 20 years. Table 01: Study variable source and description.

Table 1: Data and Variables.

Variables	Description	Log Form	Unit of Measurement	Data Source
EFP	Ecological Footprint	LEFP	Gha per person	GFN (2021)
GDP	Gross Domestic Product	LGDP	Current US$	WDI (2023)
DGE	Digital Economy	LDGE	ICT goods imports (% of total imports)	IMF (2023)
REN	Renewable Energy	LREN	Renewable Energy Consumption (% of total energy consumption)	WDI (2023)
NRE	Non-renewable Energy	LNRE	Fossil Fuel Energy Consumption (% of total energy consumption)	WDI (2023)
POP	Population	LPOP	Population, total	WDI (2023)

3.2. Theoretical Framework and Model Specification

The STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) framework is a widely recognized theoretical model for analyzing the environmental impact of socio-economic and technological factors (York et al.2003). Unlike the deterministic nature of IPAT, STIRPAT models the relationship between variables using regression techniques, accommodating non-linearities and interactions among factors (Yan, 2024). In this study, the STIRPAT framework is applied to examine the ecological footprint (EFP) of GCC countries from 2000 to 2021. The dependent variable, ecological footprint (LEFP), serves as a proxy for environmental impact. Population (LPOP) captures demographic pressures, reflecting how population size influences resource use and environmental degradation. Affluence is represented by GDP (LGDP), measuring economic output and its contribution to environmental strain through increased consumption. The technological component is split into two dimensions: Digital Economy (LDGE), representing technological advancements, and energy mix, comprising Renewable Energy (LREN) and Non-renewable Energy (LNRE), which highlight the environmental consequences of energy consumption patterns. By incorporating these variables, the STIRPAT model enables an investigation of both individual and combined effects of population, economic growth, digitalization, and energy composition on the ecological footprint. The use of log-transformed variables aligns with STIRPAT's emphasis on elasticity estimation, allowing for proportional analysis of impacts. This application of the STIRPAT framework provides a robust theoretical basis for understanding the drivers of ecological sustainability in the GCC region. The theoretical format can be illustrates in Equation 01:

$$I = \alpha P_i^{\beta} A_i^{\gamma} T_i^{\Theta} e_i \qquad (1)$$

$$LnI_i = Ln\alpha + \beta Ln(P_i) + \gamma Ln(A_i) + \Theta Ln(T_i) + e_i \qquad (2)$$

Where the anticipated parameters of the model are β, γ, and Θ, and e_i represents the disturbance term. Now, substituting the corresponding variable in Equation (2), we can write Equation (3) as follows:

$$LEFP_{it} = \alpha_{it} + \beta_1 LGDP_{it} + \beta_2 LDGE_{it} + \beta_3 LRE_{it} + \beta_4 LNRE_{it} + \beta_5 LPOP_{it} + €_{it} \qquad (3)$$

Where β_1 to β_2 are coefficients used in Equation (3)

3.3. Econometric Framework

3.3.1. Cross Sectional Dependence Test

The Cross-Sectional Dependence (CSD) test is a statistical technique used to determine whether variables in a panel dataset are influenced by common factors or exhibit interdependencies across cross-sectional units, such as countries or regions. This is crucial in studies involving panel data, as ignoring cross-sectional dependence can lead to biased estimates and invalid statistical inferences. For instance, in the context of GCC countries, shared economic, geographical, and policy dynamics could result in correlated variables across nations. Testing for CSD helps identify such correlations and ensures the selection of appropriate econometric models, such as second-generation panel data methods, to account for these interdependencies. This study employed CSD test developed by Pesaran (2007) to detect CSD issues. Equation (2) used as framework of CSD test:

$$CSD = \sqrt{\frac{2T}{N(N-1)N}\left(\sum_{i=1}^{N-1}\sum_{K=i+1}^{N}\widehat{Corr_{\iota,t}}\right)} \dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

3.3.2. Panel Unit Root test

This study employs both first-generation and second-generation panel unit root tests to examine the stationarity of variables. The Im-Pesaran-Shin (IPS) test, a first-generation method, assumes cross-sectional independence and checks for unit roots across panel data by allowing heterogeneity in autoregressive parameters. However, given the likelihood of cross-sectional dependence in GCC countries due to shared economic, environmental, and policy factors, second-generation tests like the Cross-sectional Augmented Dickey-Fuller (CADF) and Cross-sectional Im-Pesaran-Shin (CIPS) are utilized. These tests address cross-sectional dependence by incorporating cross-sectional averages in the testing procedure, making them more robust and reliable for data influenced by common shocks or interconnected dynamics. Combining these approaches ensures a comprehensive assessment of stationarity and improves the validity of subsequent analyses. The equation underlying the IPS unit root test as follows:

$$\Delta Y_{i,t} = \beta_i + \gamma_{i,t} + \delta y_{i,t-1} + \sum_{j=1}^{k}\theta_k \Delta y_{i,t-j} + \mu_{i,t} \qquad (7)$$

The CIPS test is examined using equation (8):

$$CIPS = \frac{1}{N}\sum_{t=1}^{N} t_1(N,T) \dots\dots\dots\dots\dots\dots\dots\dots\dots (8)$$

Where, N means a cross sectional aspect and T meansa time series dimension. Moreover, equation (8) provides the following method for computing the CADF:

$$\Delta Yi_t = \delta_i + \rho iYi_{t-1} + \delta i\bar{Y}_{t-1} + \sum_{j=1}^{\vartheta}\omega_{ij}\bar{Y}_{t-1} + \sum_{j=1}^{p}\alpha_{ij}\,\Delta Y_{i,t-1} + \varepsilon_{it} \dots\dots\dots (9)$$

Where, $\bar{Y}_{t-1}$, and $\Delta Y_{i,t-1}$ symbolize the average values of the cross-sectional analysis for both the first difference and lag.

3.3.3. Panel Cointegration Test

This study employs the panel cointegration test developed by Westerlund and Edgerton (2008) to examine the long-run equilibrium relationships among the variables. This test is particularly suited for panel data with cross-sectional dependence and heteroskedasticity, as it uses a bootstrap methodology to provide robust results. By testing the null hypothesis of no cointegration, it identifies whether the variables, despite being non-stationary, move together in the long run. The Westerlund and Edgerton test is crucial in this study to confirm the existence of a stable long-term relationship between the ecological footprint and its determinants—GDP, digital economy, energy mix, and population—within the GCC countries, accounting for shared regional dynamics and shocks.

$$G_t = \frac{1}{N}\sum_{j=1}^{N}\frac{\Theta_j^{f}}{SE\Theta_j^{f}} \qquad (8)$$

$$G_a = \frac{1}{N}\sum_{j=1}^{N}\frac{T_j^{f}}{\Theta_j^{f}(1)} \qquad (9)$$

$$P_t = \frac{\Theta_j^{f}}{SE(\Theta^{f})} \qquad (10)$$

$$\Theta^{f} = \frac{P_a}{T} \qquad (11)$$

$\Theta^{f} = \frac{P_a}{T}$ Shows the ratio of correction yearly.

3.3.4. Panel Autoregressive Distributive Lag (ARDL) Model

The Panel Autoregressive Distributed Lag (ARDL) model is a versatile econometric tool for analyzing relationships among variables in panel data, especially when the data exhibits mixed integration orders (I(0) and I(1)). Unlike traditional approaches that often require all variables to be stationary at the same level or deal strictly with cointegrated data, the Panel ARDL model can handle datasets with diverse integration properties without pre-testing for unit roots. It allows the estimation of both short-run and long-run dynamics in a unified framework, making it ideal for examining persistent relationships over time while capturing transient variations. The long-run equation can be presented as Equation 12:

$$\begin{aligned} LEFP_{it} = {} & \varphi_0 + \varphi_1 \mathrm{LGDP}_{\mathrm{it-1}} + \varphi_2 LDGE_{it-1} + \varphi_3 LREN_{it-1} + \varphi_4 LNRE_{it-1} + \varphi_6 LPOP_{it-1} \\ & + \sum_{i=1}^{w} \aleph_1\, \Delta LEFP_{\mathrm{it-i}} + \sum_{i=1}^{w} \aleph_2\, \Delta \mathrm{LGDP}_{\mathrm{it-i}} + \sum_{i=1}^{w} \aleph_3 \Delta \mathrm{LDGE}_{\mathrm{it-i}} + \sum_{i=1}^{w} \aleph_4\, \Delta\, LREN_{it-i} \\ & + \sum_{i=1}^{w} \aleph_5 \Delta \mathrm{LNRE}_{\mathrm{it-i}} + \sum_{i=1}^{w} \aleph_6 \Delta \mathrm{LPOP}_{\mathrm{it-i}} + \varepsilon_t \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12) \end{aligned}$$

After long-term connections are established, the error correction model (ECM) is utilized to evaluate the Error Correction Term (ECT) and short-term correlations. The short-run equation for Panel ARDL model can be showed as follows:

$$\begin{aligned} LEFP_{it} = {} & \aleph_0 + \sum_{j=1}^{w} \aleph_1 \Delta \mathrm{LEFP}_{\mathrm{it-j}} + \sum_{j=1}^{w} \aleph_2 \Delta \mathrm{LGDP}_{\mathrm{it-j}} + \sum_{j=1}^{w} \aleph_3 \Delta \mathrm{LDGE}_{\mathrm{it-j}} + \sum_{j=1}^{w} \aleph_4 \Delta\, REN_{\mathrm{it-j}} \\ & + \sum_{j=1}^{w} \aleph_6 \Delta \mathrm{LNRE}_{\mathrm{it-j}} + \sum_{j=1}^{w} \aleph_6 \Delta \mathrm{LPOP}_{\mathrm{it-j}} + \forall ECT_{\mathrm{it-j}} + \varepsilon_t \qquad (13) \end{aligned}$$

Where, ∀ is the rate of adaptation.

3.3.5. Robustness Check

This study incorporates the Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CCEMG) estimators as robustness approaches to ensure the reliability of results. The AMG method accounts for heterogeneity and cross-sectional dependence by incorporating a common dynamic process across panel units, making it suitable for data influenced by shared global or regional shocks. Similarly, the CCEMG estimator addresses cross-sectional dependence by including cross-sectional averages of the regressors and dependent variable, thus mitigating bias arising from omitted common factors. Employing these advanced estimators allows the study to validate the robustness of the relationships between ecological footprint and its determinants—GDP, digital economy, energy mix, and population—while accounting for the unique characteristics of GCC countries' panel data.

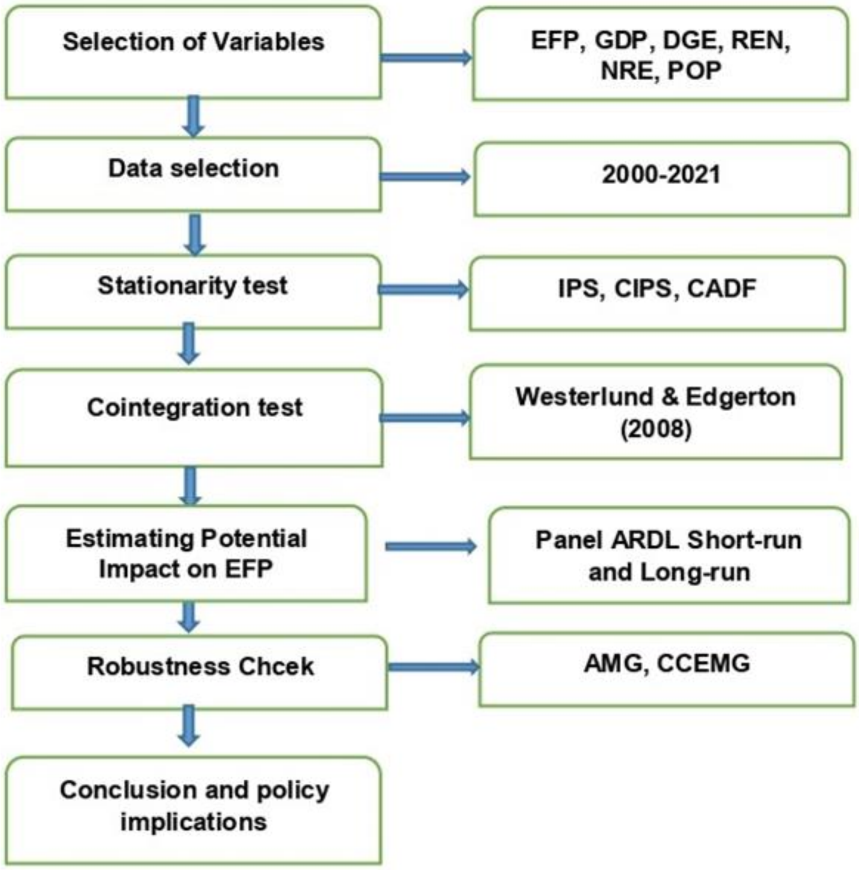

Figure 1:

4. RESULTS AND DISCUSSION

The summary statistics provide an overview of the key variables in the analysis, based on 132 observations spanning GCC countries from 2000 to 2021. The ecological footprint has a mean of 2.111 with moderate variability (0.356) and ranges from 1.172 to 2.771. GDP averages 10.349 with a standard deviation of 0.454 and ranges from 9.784 to 11.594, indicating relatively stable economic output across the sample. Digital economy values show a mean of 1.627 with variability (0.454) and range from 0.329 to 2.844. Renewable energy and non-renewable energy exhibit means of 2.961 and 4.21, respectively, showing a higher reliance on non-renewable sources. Population has the highest variability (1.097), averaging 14.872 and ranging from 13.365 to 17.267, reflecting significant demographic differences among the countries. The time period centers around 2010.5, covering years from 2000 to 2021, while the identifiers reflect six distinct units corresponding to the countries. These statistics highlight the variability and scale of the variables, providing a foundation for exploring their relationships with ecological sustainability.

Table 2: Summary Statistics.

Variable	Obs.	Mean	Std. Dev.	Min.	Max.
ID	132	3.5	1.714	1	6
T	132	2010.5	6.368	2000	2021
LEFP	132	2.111	.356	1.172	2.771
LGDP	132	10.349	.454	9.784	11.594
LDGE	132	1.627	.454	.329	2.844
LREN	132	2.961	.723	1.548	4.059
LNRE	132	4.21	.376	3.224	4.586
LPOP	132	14.872	1.097	13.365	17.267

The CSD test demonstrates high dependence between variables with highly significant p-values across all tests. This means that the ecological footprint and its parameters such as GDP, digital economy, renewable energy, non-renewable energy, and population are governed by common or related processes in GCC nations. These results highlight the need to consider cross-sectional dependence in the analysis to ensure robust and consistent econometric modeling.

Table 3: Cross Sectional Dependence test.

Variables	Statistics	P Value
LEFP	2.30**	0.021
LGDP	3.42***	0.000
LDGE	5.68***	0.000
LREN	5.25***	0.000
LNRE	4.38***	0.000
LPOP	17.61***	0.000

The panel unit root test results are summarized in Table 4. The results show that in the context of both the first-generation and second-generation unit root tests, all the variables, except LDGE, are non-stationarity at their scales. But they remain fixed after first differencing, exhibiting integration at order one (I(1)). On the other hand, LDGE is static at its level, which makes it an I(0) variable. For example, the variables LEFP, LGDP, LREN, LNRE and LPOP are integrated at order one, which means they reach stationarity only once they differ. This means that they are subject to stochastic variations at each level but settle down when transformed. LDGE, on the other hand, needs no differencing, and is intrinsically stationary, so it does not exhibit this kind of behaviour. These findings ensure that all of the variables in the study are unaffected by unit root errors, thus guaranteeing the stability of the analysis. The I(0)/I(1) combination points towards the need for thorough tests to validate the integration order and to guide the choice of econometric methods for further modelling and inference.

Table 4: First and Second generation panel unit root test.

Variables	IPS		CIPS		CADF		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LEFP	-1.342	-4.234***	-0.971	-4.031***	-0.865	-3.971***	I(1)
LGDP	-0.341	-3.650***	-0.654	-3.703***	-0.704	-4.080***	I(1)
LDGE	-3.021**	-4.891***	-2.987**	-5.461***	-3.084**	-4.972***	I(0)
LREN	-0.431	-3.545***	-0.287	-3.871***	-0.502	-3.981***	I(1)
LNRE	-1.054	-4.541***	-0.517	-5.981***	-0.601	-4.781***	I(1)
LPOP	-1.261	-4.091***	-1.062	-4.682***	-1.402	-4.567***	I(1)

The panel cointegration test results shown in Table 5 confirm a long-term equilibrium relationship between the panel's variables. The test results (Gt, Ga, Pt, Pa) all have significant p-values (less than 0.05), which validates the null hypothesis of no cointegration. In particular, Gt and Ga have highly significant p-values (0.003 and 0.000 respectively), and the Pt and Pa also have p-values (0.034 and 0.023 respectively) that support this conclusion. Collectively, these results suggest that the variables evolve together in the long term, making them suitable for processing in a cointegration approach.

Table 5: Panel Cointegration test.

Statistic	Value	Z-Value	P-Value
G_t	-2.3561	1.8923	0.003
G_a	-3.7812	2.9710	0.000
P_t	-2.9012	1.9820	0.034
P_a	-4.7823	2.0912	0.023

The Panel ARDL model results in Table 6 are extremely informative on the short and long-term relationship between ecological footprint and major variables, such as economic growth, digital economy, renewable energy, non-renewable energy, and population, in the GCC region. The relationship between economic growth (LGDP) and ecological footprint (LEFP) is remarkably positive, with a 1% increase in LGDP causing a long-term increase in LEFP of 0.111% and a short-term increase in LEFP of 0.383%. This concurs with prior work (for example, Hassan et al. (2019), Ahmad et al. (2020), Addai et al. (2022), Voumik et al. (2023a), Chen et al. (2023), and Ridwan et al. (2024a), which also discovered that high-growth economies degrade the environment faster. Such findings reveal that, although economic growth helps develop, it comes at high environmental costs, underscoring the importance of green policies for sustainable growth. In contrast, the digital economy (LDGE) has a high negative effect on LEFP, where a 1% increase in LDGE decreases LEFP by 0.087% long-term and 0.025% short-term (as shown by Raihan et al. (2024a) and Rahman et al. (2024) that digitalisation can mitigate environmental impacts through better efficiency and technological innovation. But the modest short-run effect could reflect temporary impediments to digital adoption and suggest the need for policies to foster digital adoption and sustainable usage. LREN also negatively impacts LEFP: a 1 % increase in LREN will decrease LEFP by 0.290% in the long run and 0.236% in the short run, as demonstrated by Pattak et al. (2023), Polcyn et al. (2023), Raihan et al. (2023a), and Ahmad et al. (2024), which emphasizes the use of renewable energy for ecological footprint reduction and environmental sustainability. This underscores the need to invest in renewable energy infrastructure and supportive policies in order to secure long-term ecological gains. Non-renewable energy (LNRE), however, has a high environmental impact; a 1% growth in LNRE causes a long-run increase of 0.731% and a short-run increase of 0.847%, as reported by Voumik et al. (2023b), Raihan et al. (2024b), who wrote about the environmental horrors of fossil fuel dependence. The larger short-run effect reflects the short-term environmental costs of fossil-fuel use and suggests that GCC nations should diversify their energy portfolios and shift towards more environmentally sustainable sources. In addition, the positive correlation between LEFP and population growth (LPOP) is strong: for every 1% LPOP increase, LEFP grows by 0.125% over the long run and by 0.628% over the short run, as reported in Onwe et al. (2024) and others, associate population growth with greater environmental stresses as a result of growing demand and use for resources. This more severe short-run effect could reflect the accelerated urbanisation and high consumption rates that characterise GCC nations, and require coordinated planning to contain population growth and its environmental impacts.

Table 6: Results of Panel ARDL Method.

Long-run Estimation **Variable**	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.***
LGDP	0.111	0.031502	3.54502	0.0006
LDGE	-0.087	0.039202	-2.2326	0.0282
LREN	-0.290	0.123105	-2.35706	0.0207
LNRE	0.731	0.383159	1.90831	0.0197
LPOP	0.125	0.050628	2.47088	0.0155
Short-run Estimation				
COINTEQ01	-0.494	0.163047	-3.03572	0.0032
D(LGDP)	0.383	0.090944	4.21303	0.0001
D(LDGE)	-0.025	0.049259	0.525454	0.6006
D(LREN)	-0.236	0.113471	2.083364	0.0402
D(LNRE)	0.847	0.959903	1.924182	0.0577
D(LPOP)	0.733	0.262109	2.798676	0.0063
C	3.628	1.548238	2.989843	0.0036

The AMG and CCEMG estimates, used to validate the Panel ARDL results are reported in Table 7. Results consistently indicate that economic development, non-renewable energy, and population positively impact the ecological footprint and are thus the major causes of environmental degradation in the GCC. By contrast, renewable energy and digitalisation show a significant negative correlation with environmental impact, which suggests that they can offset environmental impacts through cleaner energy consumption and technologically optimized efficiency. That AMG and CCEMG estimates fit the Panel ARDL results proves the robustness of the initial results and reassures us that the relationships we observed are reliable. The verification by AMG and CCEMG also bolsters the validity of Panel ARDL, offering strong proof that they are the fundamental drivers of the ecological footprint in the GCC. This homogeneity between estimation methods highlights the need for convergent policy interventions focused on economic growth, energy transition and demographic change to achieve ecological viability.

Table 7: Results of Robustness check.

Variables	AMG	CCEMG
LGDP	0.271***(0.0541)	0.198***(0.0674)
LDGE	-0.041**(0.3981)	-0.098***(0.4920)
LREN	-0.381**(0.1092)	-0.185***(0.1894)
LNRE	0.607***(0.2094)	0.598***(0.3120)
LPOP	0.134**(0.0349)	0.159* (0.5629)
C	4.658***(1.7809)	3.894***(1.5937)

5. CONCLUSION AND POLICY RECOMMENDATION

This research examines the effects of economic development, digitalisation and energy mix on the carbon footprint of the GCC over the 2000–2021 period. We used a rigorous econometric approach, beginning with several pre-estimation tests, such as the Cross-Sectional Dependence (CSD) test and first- and second-generation panel unit root tests. The pre-estimation results indicate that although the variables are not prone to unit root issues, they do have major CSD problems, indicative of how the GCC economies are networked. They used the panel cointegration test to check for long-run relations: the variables were cointegrated and there was stable long-term equilibrium. In order to capture both short-run and long-run dynamics, the paper used the Panel ARDL technique. The data show that economic growth, fossil fuels and population are highly positively correlated with the footprint, and are therefore among the major drivers of GCC environment degradation. In contrast, renewable energy and the digital economy have significant negative correlations with the ecological footprint, thereby potentially reducing environmental impacts and facilitating sustainability. In order to make sure that Panel ARDL results were valid and robust, other estimates were computed using the AMG and CCEMG techniques. Such validation methods assured the robustness of Panel ARDL findings and strengthened the validity of study findings.

In order to combat the environmental pressures identified in this paper, GCC policymakers should give a strong emphasis to a full transition to sustainable development. Green economic development should involve encouraging efficient industries and rewarded firms to implement greener technologies. We must move quickly to renewables, investing in more solar, wind and other renewable energy sources, and adopting policies that allow the private sector to become more engaged in the renewable energy space. At the same time, digitalisation should help improve energy performance, save resources and support smart technologies for sustainable urban development. Given the important role that non-renewable energy plays in driving up the ecological cost, fossil fuels should be phased out over time through carbon price and subsidy removal for non-renewable energy. We can slow down the growth and urbanisation by creating sustainable infrastructure, enabling energy-efficient homes and integrating green features into urban design. These include education efforts and public outreach programs that would foster environmentally friendly behaviour at both the personal and social levels. Policymakers will also need to strengthen regional cooperation within the GCC to exchange lessons learned, pool investments in renewable energy initiatives, and establish coordinated mechanisms for long-term environmental resilience. Such targeted measures will allow GCC states to strike a balance between economic development and environmental protection for a future that is environmentally resilient.

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