The environmental variations compel global countries for restructuring economic growth policies to ensure reliable energy usage. Ecological sustainability is a leading concern of the world for adequate and smooth survival of human beings. The inefficiency of technology is a focal hindrance to attaining the sustainable environment goal. This research aims to probe the cointegration and causal relationship among information communication technology, CO2 emission, economic development, trade, and total population for GCC countries, namely, the United Arab Emirates, Saudi Arabia, Qatar, Oman, Kuwait, and Bahrain, from 2000 to 2018. This research approached the unit-root tests, cointegration test, and FMOLS and DOLS test to determine stationarity of data series, cointegration relationship among variables, and the short- and long-run relationship among variables, respectively. The results of the analytical procession by employing FMOLS and DOLS confirmed that CO2 emission, ICT, and ED are positively significant, while POP was negatively substantial at a 1% level. No relation has been observed between trade and CO2 emission. The long-run relationship among variables is confirmed by FMOLS and DOLS analyses. A negative relationship between population growth and CO2 emission is observed. It is ideal for enhancing environmental sustainability by awareness of people’s importance to the environment. The GCC countries should transform or divide their economic growth sectors instead of only the fossil fuel sector. This research also enlightened the way to reduce environmental destruction by the attraction of foreign investments in other sectors compared to entire fossil fuel industries, and the information communication technologies also move toward green technology using environmentally friendly energy resources.

Keywords: environmental sustainability, ICT, economic growth, GCC countries, FMOLS, DOLS
INTRODUCTION

The Gulf Cooperation Council (GCC) countries suffer from severe environmental challenges, i.e., biosphere, hydrosphere, lithosphere, and atmospheric pollution. The last few years are evidence of environmental pollution, particularly military conflicts, constructive infrastructure, and demolition debris. Global warming has changed the picture of the globe, and this alteration comes from climate change. The increasing behavior of radioactive greenhouse gases, especially CO$_2$ emission in the atmosphere, is the leading cause of global environmental destruction (Warrick, 1988). The WWF/ecological footprint report “Our Living Planet,” a visualizer of 150 countries’ ecological states, declared that the UAE was putting the most significant footprint globally. The per capita income of the UAE countries is becoming the reason for placing heavy stress on the planet. The per person (hectares/person) total ecological footprint (TEF) for UAE is 1.8, and the aggregate figure was 11.9 global ha/person (hectares/person). In comparison, Kuwait and the Kingdom of Saudi Arabia also have enormous footprints—7.6 and 4.6 international ha/person, respectively.

The conventional monotonic reliance on the consumption of non-renewable fossil fuels has eventually generated a global agreement for guaranteeing energy security, while also minimizing the environmental consequences of fossil fuel combustion. Historically, such a heavy reliance on fossil fuels has resulted in the rapid depletion of their reserves, putting global energy sustainability goals in jeopardy. Furthermore, the finite nature of these primary energy resources has contributed to the unreliability of secondary energy supply (Kasayanond, 2019; Kunkel and Matthess, 2020). One possible explanation for this phenomenon is that worldwide power generating volumes frequently lag behind comparable installed capacity, owing to severe primary energy supply constraints. Aside from the continued depletion of non-renewable energy (NRE) reserves, rising global energy demand has also contributed to global energy crises. Furthermore, in particular, developing economies have been steadily unable to meet their distinct energy demands with domestic energy supplies. As a result, energy resource diversification is widely regarded as a vital energy sector reform for guaranteeing global energy security (Kasayanond, 2019; Kunkel and Matthess, 2020). The energy inputs are undeniably necessary for economic expansion and achieving economic welfare. However, incorporating renewables into energy systems is critical to ensure the long-term viability of socioeconomic and environmental growth. Furthermore, improving energy use efficiency, particularly in third-world countries, has become a top priority.

The word “environmental sustainability” refers to preserving natural resources and the continuous improvement of environmental quality (Kasayanond, 2019; Murshed et al., 2020). As a result, the United Nations (UN) has asked for international commitments from global stakeholders to ensure greater access to affordable, reliable, sustainable, and contemporary energy supplies worldwide, taking into account global energy security and environmental sustainability concerns (Khan et al., 2020; Murshed, 2020; Gul et al., 2021). In this regard, the seventh Sustainable Development Goal (SDG 7) aimed to significantly increase the share of renewables in global final energy consumption while also doubling energy-use efficiencies. However, multidimensional constraints often obstruct the achievement of these targets, particularly in developing economies; among these, technological redundancy in these economies is frequently hypothesized to play a negative role in bottlenecking the achievement of energy and environmental sustainability targets (Mirza et al., 2009; Urmee et al., 2009).

This research aims to contribute to the existing literature in divergent aspects. This research focused on the impact of information communication technology on environmental sustainability in GCC countries. In the last 5 years, a significant change has been observed in traditional fossil energy sources, digitalization, renewable energy, and climate change. The GCC group of countries also moves toward energy diversification to overcome the toxic emissions and make a positive contribution to environmental quality with research and initiative in digitalization, renewable energy, and economic growth. This research will help measure the change and provide fundamental structural changes to enhance the quality of the environment with the growth of the economy and global competencies by acknowledging digitalization. The cointegration and causal relationship between variables are determined by employing the FMOLS and DOLS methods. The existing literature usually focused on South Asian countries (Mursched et al., 2020) with trade openness and renewable energy. This research purposely observed GCC countries observing the potential impact of ICT on environmental sustainability and economic growth. The CO$_2$ emission is considered an ecological representative in GCC countries, selected based on previous studies with confirmation that CO$_2$ emission is an aggregated top portion of greenhouse gas emissions globally (Pachauri et al., 2014; Mursched et al., 2020).

LITERATURE REVIEW

The traditional reliance on environmentally unfriendly non-renewable energy (NRE) resources to meet global energy demand has elicited international consensus for achieving socioeconomic and environmental sustainability, mainly through optimal use of the relatively cleaner renewable energy (RE) alternatives (Khan et al., 2020; Murshed, 2020). The constant reliance on the burning of NRE resources has resulted in overexploitation of these finite resources, putting global energy security in jeopardy to a great extent. In addition, the poor supply of primary NRE resources has harmed the reliability of secondary energy supplies, particularly electricity, forcing global power plants to run at or below their installed capacity (Aye and Edoja, 2017). Technology usage causes environmental degradation to
consume resources, continuous economic development (GDP), and energy consumption (Huesemann and Huesemann, 2008). The current millennium will reduce distances of geographic boundaries and closer up the sociocultural values of the world by using information communication technology (Avom et al., 2020; Khan et al., 2020; Naseem et al., 2021a). The paradox of wealth and poverty is the creation of information communication technology (ICT) which has presented the two opposite phases of human life, i.e., a bridge between individuals and isolation. The dramatic transformation of the world via information communication technology has tied people and communities, enhanced their standard of life, and increased global opportunities, modern facilities, and up-trending productivity in the last quarter of the 21st century (Avom et al., 2020; Khan et al., 2020; Naseem et al., 2021a). The scholars and researchers consider the contribution of ICT to economic growth, gross domestic product (GDP), the better infrastructure of organizations, international trade, financial structure, employment opportunity, and systematic democracy in people of a country (Bon et al., 2016; Sarfraz et al., 2022). Undoubtedly, the ICT infrastructure has enhanced the competition for attracting foreign direct investment to reshape the growth map of the globe (Al Asbahi et al., 2019; Sun et al., 2020; Yang et al., 2021).

The developing countries have been contemplating the significant impact of FDI on economic growth and pillars of a positive picture of an individual country’s growth since 1980. The modern monetary theory also confirmed the position of FDI as a catalyst and engine of economic growth aggregately and per capita growth of a country. The economic boom and energy-intensive sector is information communication technology (ICT), i.e., computers, laptops, and mobile devices, which emitted 2% of greenhouse gases worldwide. The positive and negative effects of ICT are still under discussion. The theoretical approach has approved that ICT contributes to an up-trending graph of CO2 emission in terms of ICT machinery production, energy consumption and energy-based devices, and recycling of electronic wastage. Smarter cities, transportation systems, the grid of electricity, industrial procession, and energy-saving can help reduce CO2 emissions by environmentally friendly information communication technology (Lee & Brahmasrene, 2014; Awan et al., 2021). The relationship among ICT, CO2 emission, and economic growth is examined by designing the panel of nine ASEAN (Association of Southeast Asian Nations) countries from 1991 to 2009. A significant positive relationship between ICT, economic growth, and CO2 emission was observed (Zhang et al., 2021; Irfan et al., 2022; Zhao et al., 2022). A bidirectional relationship is also confirmed between economic growth and CO2 emission (Avom et al., 2020; Khan et al., 2020; Murshed, 2020; Mohsin et al., 2020b). A bulk of the research was conducted to determine the relationship between economic growth and CO2 emission in a few decades. Globally, many countries are antagonized with the significant challenge of developing the economy and sustainability of the environment in parallel (Tucker, 1995; Chang, 2010; Fodha & Zaghdoud, 2010; Niu et al., 2011; Sarfraz et al., 2022; Mohsin et al., 2021a). A negative long-run relationship between GDP and CO2 emission since the low-carbon emitted technology will allow output levels to be met at lower levels of CO2 emissions in the long term (Naseem et al., 2019; Mohsin et al., 2022).

The short-run positive link between GDP and CO2 emission is observed with rapid production growth and high energy consumption for technology use. The estimation of ECM declared that the GDP is negatively related to CO2 emission and suggested that the low-carbon and environmentally friendly technology can achieve the same production level at lower emissions (Kasperowicz, 2015). Divergent research studies (Tucker, 1995; Chang, 2010; Fodha & Zaghdoud, 2010; Niu et al., 2011) determined the linear relationship between economic growth and environmental destruction. The findings of empirical analysis have acknowledged a causal relationship present among carbon emission, energy consumption, electricity production process, fossil fuels, and growth of GDP. The developing countries do not present a significant connection between CO2 emission and GDP, while developed countries show a strong association between these variables.

### DATA DESCRIPTION

Carbon dioxide (CO2) emissions, economic development (ED), information communication technology (ICT), trade (TR), and total population (POP) of the Gulf Cooperation Council countries are all examined in this study on an annual basis. From 2000 to 2018, the World Bank (WB) has provided analytical data series retrieved from its website. The World Bank’s official website offers data at several scales, which is why the data specifications for this research are presented in Table 1.

### MATERIALS AND METHODS

The main model of this research is given as follows:

\[
CO_{2t} = \beta_0 + \beta_1 ICT + \beta_2 ED + \beta_3 TR + \beta_4 POP + \varepsilon_t, \quad (1)
\]

In the aforementioned Eq. 1, the sign of delta \( \Delta \) used for the first difference, while \( \beta_0, \beta_1, \beta_2, \beta_3, \) and \( \beta_4 \) are demonstrated as the independent parameters. The abbreviation of variables in the equation is representative of environmental degradation (CO2), information communication Technology (ICT), economic development (ED), trade (TR), and total population (POP). \( \varepsilon_t \) is an error term with respect to time. The analytical process of this research will start to determine the stationarity of the panel data set by using four renowned panel unit root tests (PURTs), i.e., ADF, PP, LLC, and IPS. To obtain the stationarity of the data series, the cointegration technique is used to check the relationship among selected variables. The confirmation of cointegration allowed processing of the data series to determine the long-run elasticities by employing FMOLS. The dynamic OLS (DOLS) is used to observe the short- and long-run dynamic series. The last step of this analytical process is variance decomposition which will check the cross contribution among all the variables, not only the behavior
The inclusion of $\alpha$ Panel ADF-statistic $-ED$ GDP (current US$) World Bank ICT Information communication technology (ICT) (% of total goods) World Bank POP Total population World Bank Table 3 | Cointegration tests.

| Variable | Within-dimension | Between-dimension |
|----------|-----------------|-------------------|
| Panel v-statistic | 0.994 | — |
| Panel rho-statistic | 2.169 | 2.845 |
| Panel PP-statistic | 0.985 | 0.998 |
| Panel ADF-statistic | $-5.293^*$ | $-5.919^*$ |

Note: *, **, and *** denote 1%, 5%, and 10% level of significance.

The determination of variable sequence stability indicates the Pedroni intercept and trend coefficient heterogeneous panel cointegration test (Pedroni, 1999; Pedroni, 1999). The Pedroni–Engle–Granger-based cointegration test regression equation is as follows:

$$CO_{2t} = \alpha_1 + \delta_t + \beta_1 ICT_{it} + \beta_2 ED_{it} + \beta_3 TR_{it} + \beta_4 POP_{it} + \epsilon_{it},$$

(5)

The deterministic trend of each country is represented by $\alpha_1$, $\delta_t$; and the residuals as deviations from the long-run relationship are represented by $\epsilon_{it}$. $\beta_1$ is the coefficient of information communication technology, $\beta_2$ for economic development, $\beta_3$ for trade, and $\beta_4$ for population. The residuals are computed under the null (no cointegration) and alternative (cointegration) hypotheses. $\epsilon_{it} = I(1)$ and $\epsilon_{it} = I(0)$, respectively. The integration of regression’s residuals at first difference $I(1)$ is computed by applying the auxiliary regression. The auxiliary regression is presented as follows:
TABLE 4 | Estimated FMOLS and DOLS.

| Regressor | Coefficient | t-statistic | Prob. | Coefficient | t-statistic | Prob. |
|----------|-------------|------------|-------|-------------|------------|-------|
| ICT      | 0.031*      | 0.000      | 0.000 | 0.025*      | 0.000      | 0.010 |
| ED       | 0.192*      | 0.000      | 0.000 | 0.189*      | 0.000      | 0.001 |
| TR       | 0.014       | 0.000      | 0.880 | 0.031       | 0.000      | 0.132 |
| POP      | 0.281*      | 0.054      | 0.000 | 0.031       | 0.073      | 0.002 |

Note: *, **, and *** denote 1%, 5%, and 10% level of significance. OLS, ordinary least square.

TABLE 5 | Variance decomposition of CO₂ emissions.

| Period | SE   | Ln CO₂ | Ln ICT | Ln ED | Ln TD | Ln POP |
|--------|------|--------|--------|-------|-------|--------|
| 1      | 0.048| 100    | 0.000  | 0.000 | 0.000 | 0.000  |
| 2      | 0.069| 98.265 | 0.016  | 0.500 | 0.591 | 0.627  |
| 3      | 0.083| 95.977 | 0.440  | 0.604 | 0.916 | 2.064  |
| 4      | 0.094| 93.003 | 1.243  | 0.586 | 0.986 | 4.182  |
| 5      | 0.104| 89.233 | 2.413  | 0.587 | 0.928 | 6.841  |
| 6      | 0.113| 84.666 | 3.996  | 0.653 | 0.829 | 9.857  |
| 7      | 0.129| 79.449 | 5.966  | 0.823 | 0.729 | 13.033 |
| 8      | 0.129| 73.829 | 8.211  | 1.135 | 0.643 | 16.181 |
| 9      | 0.136| 68.081 | 10.575 | 1.615 | 0.581 | 19.147 |
| 10     | 0.144| 62.449 | 12.907 | 2.269 | 0.553 | 21.823 |

\[ \mu_{it} = \mu_{it} - \frac{L_{21i}^2}{L_{22i}} X_{it} \Delta X_{it}, \hat{y}_i = \hat{\Gamma}_{21i} \Omega_{21i}^g, L_i \text{ was lower triangulation of } \hat{\Omega}_i. \]

The asymptotic distribution of FMOLS \( \hat{\beta}_{\text{FMOLS}} = \left( \frac{\sum_{i=1}^{N} \sum_{t=1}^{T} X_{it} X_{it}^T}{\sum_{i=1}^{N} \sum_{t=1}^{T} \Delta X_{it} \Delta X_{it}^T} \right)^{-1} \right) \) and DOLS \( y_{it} = a + bX_{it} + \sum_{j=k} \Delta \hat{\phi}_j X_{it} + \epsilon_{it} \) estimator is the same, which performed and confirmed the consistency of outcomes.

EMPIRICAL RESULTS

The results of the panel unit root tests (PURTs) are presented in Table 2, which confirmed the stability of the data series. Four unit root tests are applied to the selected data span of variables for assurance of result accuracy. The data series have gone through level and first difference by getting the mixture of results (Mohsin et al., 2021a). Some tests confirmed significance at level, but some tests denied it while all panel unit root tests show their significance at 1%, 5%, and 10% at first difference. The mixture of results is provided with a feasible and perfect condition to implement the cointegration test.

Table 3 shows the results of the Pedroni–Engle–Granger-based cointegration test. According to Engle and Granger (1987), the residuals of spurious regression were performed at first difference integration I(1) to examine variable integration. The cointegration of variables was performed at the first difference I(1), and then residuals should be integrated at level I(0) and vice versa (Mohsin et al., 2021b). Pedroni (1999) extended the Engle–Granger framework with the inclusion of two alternative hypotheses, i.e., within-dimension and between-dimension. The PP and ADF tests are significant at 1% under within-dimension and between-dimension. These alternative hypotheses in Pedroni cointegration are used to check homogeneity and heterogeneity among the variables.

The results of FMOLS and DOLS are presented in Table 4. Pursely, the FMOLS is used to check the long-run elasticity of the panel, and DOLS is applied for robust check of a small sample. The FMOLS eliminated the problems caused by the long-run correlation between the cointegration equation and stochastic regressor innovation. The leading feature of FMOLS is having an asymptotically unbiased estimator (Phillips and Hansen, 1990; Jamil et al., 2021; Ivascu et al., 2021). The DOLS is used to cross-
check OLS and FMOLS, and the endogeneity biases are also controlled by it. The FMOLS and DOLS estimators provide similar results for the variables, i.e., ICT, ED, and TR, across all sample countries regarding statistical significance. Still, the magnitudes of the predicted coefficients are slightly different.

Except for trade, all coefficients are statistically significant at the 1% significance level. The results declared a positive relationship between CO₂ emission, information communication technology, and economic development, while a negative relationship was confirmed for trade by FMOLS and DOLS. According to the results of FMOLS, 1% increase in ICT and ED will increase CO₂ emission by 0.0306% and 0.1920%, respectively, while a 1% increase in total population decreases CO₂ emission by 0.2809%. The total population decreases the CO₂ emission because people are beginning to realize the global environmental situation, and they are trying to reduce their carbon footprint as an individual body. They are more conscious of environmentally friendly technologies. The DOLS also confirmed the same results as FMOLS that a 1% increase in ICT and ED shows an increasing trend in CO₂ emission by 0.0245% and 0.1889%, respectively. Trade is shown as an insignificant behavior toward CO₂ emission, while a significant negative relationship between the total population and CO₂ emission is observed at a 1% level. In GCC countries, the population and trade are not directly affecting environmental sustainability. The information communication technology is based on energy, and the economic development of GCC countries is also based on oil consumption which are the main sectors of environmental degradation.

Table 5 contains the results of variance decomposition, which is used to determine the contribution of each variable to others or its counterpart (Helmut, 2005; Naseem et al., 2021b). CO₂ emission has shown a downward trend, while information communication technology, economic development, and total population have shown an upward trend. The behavior of trade shows a downward trend. The decomposition analysis results
confirmed the reduction in CO₂ emission concerning variability in the rest of the variables. The impulse response is used to measure the impact of one standard deviation shock on an independent variable that causes an upward (downward) reaction in dependent variables in a specific time period. The graphic representations of impulse response are available in

FIGURE 2 | Response to Cholesky One S.D Innovations.
Figure 2. The behavior of individual variables toward other variables is easily visualized in Figure 2.

CONCLUSION AND DISCUSSION

This research examined the cointegration and causal relationship among information communication technology, CO₂ emission, economic development, trade, and total population for GCC countries, namely, the United Arab Emirates, Saudi Arabia, Qatar, Oman, Kuwait, and Bahrain, from 2000 to 2018. The cointegration among selected variables was examined by employing FMOLS and DOLS analyses. FMOLS results declared that CO₂ emission, ICT, and ED are positively significant, while POP was negatively substantial at the 1% level. No relation can be observed between trade and CO₂ emission. The long-run relationship among variables is confirmed by FMOLS and DOLS analyses. The population growth of GCC countries was inversely related to CO₂ emission because the people are conscious of environmental sustainability. They focused on environmentally friendly technology and renewable energy used as a replacement for fossil fuels, reducing the footprint of CO₂ emission. There is an increasing behavior of information communication technology and economic development toward CO₂ emission in GCC countries because the energy source of these countries is fuel consumption. The economic growth is also based on fossil fuels which comparatively enhance the CO₂ footprint. The impulse response also confirmed an upward relationship among variables and CO₂ emission, as confirmed by FMOLS and DOLS. The CO₂ emission can be reduced by transforming leading sectors of the economy. Renewable energy, green technology, and the transformation of energy sources compared to fuel consumption can reduce greenhouse gas emissions. As a result of the findings, it was concluded that the efficient utilization of renewable energy would minimize GHG emissions over time. As provided in the study’s preceding parts, the prior literature has typically established a positive association between ICT, ED, and CO₂ emissions; however, few studies have examined the relationship between ICT and CO₂ emissions. This research gap was filled for the first time, and the overall link between information and communication technology and CO₂ emissions was negative. In the short run, the connection between ICT and CO₂ emissions for GCC countries was shown to be the same.

Official Environmental Protection Bodies in the GCC Countries

The GCC countries are keenly concerned about environmental protection and the enhancement of ecological preservation. The GCC countries designed divergent international and regional panels to maintain the environmental quality with the growth of the individual sector of the economy. The newly organized agencies, councils, and ministries, especially environmental check and balance, are significantly playing their roles. These institutional bodies have collaborated with governments, researchers, environmentalists, and policymakers by taking part in the decision-making process regarding environmental priorities, challenges, threats, and problems in GCC countries. The institutional bodies with the executive agency working on environmental sustainability in different GCC countries are given as follows:

- In Bahrain—the Policy Institute of Environment and Wildlife affairs with the executive agency, the Public Commission for the Protection of Marine Resources, Environment, and Wildlife.
- In Kuwait—the Policy Institute of Environment Public Authority with the executive agency, Environment Public Authority.
- In Oman—the Council of Ministries’ Policy Institute with the executive agency, Ministry Environment and Climate Change.
- In Qatar—the Policy Institute of the Council of Ministers (Permanent Commission for Environmental Protection) with the executive agency Supreme Council for the Environment and Natural Reserves.
- In Saudi Arabia—the Policy Institute of the Ministerial Committee on Environment with the executive agency, Presidency of Meteorology and Environment (PME).
- In UAE—the Policy Institute of the Council of Federation with the executive agency, Federal Environment Agency/Ministry of Environment and Water Resources.

Recommendations, Future Direction, and Limitations

This research suggested that a rapid increase in information communication technology (ICT) and growth of the economy’s activities can consequently increase CO₂ emissions. Renewable energy might be more expensive than fossil fuel energy in developed and developing countries, but renewable and environmentally friendly energy resources should be prioritized. Renewable energy and environmentally friendly resources are undoubtedly expensive but they can enhance environmental quality and lower pollution levels. Technically, the expensive renewable and low-carbon-emitted points and subordinate financing activities like reducing pollution and enhancing environmental quality are more beneficial. The inclusion of many factors can raise renewable energy as cost reductions due to renewable energy technologies, dedicated legislative initiatives, improved access to energy resources, environmental concerns, and emerging nations’ expanding energy needs.

The Gulf Cooperation Council countries can be attained a sustainable environment by following pedagogical innovation and awareness of low carbon technology. The primary energy source of fossil fuels is decentralized with hydropower, solar power, wind energy, biomass, and geothermal energy. The CO₂ and ultraviolet greenhouse gas emissions are strengthened by fossil fuels and destroy environmental sustainability. The energy-saving and energy conservation program can practically enhance the ecological quality of GCC countries. The future direction of this research should focus on the
circular economy’s principle and clean energy development mechanisms integrated with renewable energy information communication technologies. The lack of experience in environmental authorities and institutional capacity became the hurdle to implementing most ecological precautions. Many approved policies and structural changes are in the pipeline to improve awareness, protection, and sustainability of the environment. The current need is to enhance the expertise and skillful environmentalists who can apply the new structural changing to attain the goal of green GCC countries. The green technology to enter digital economic growth with no carbon emission protocol should be followed by GCC countries. This research is limited in the methodological perspective, which can be explored in future with the second generation of econometric methodology. The GCC countries should be compared with different groups of countries such as BRICS, G-20, and random global countries.

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DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. These data can be found at: https://databank.worldbank.org/source/world-development-indicators.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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