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Environmental Sustainability in Technologically Advanced Economies: The Role of Eco-Digitalization, Green Finance, and Green Technology

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Abstract

This study investigates the effects of eco-digitalization, green technology, and green finance on environmental sustainability in the presence of affluence and population. The sample size consists of a panel of 19 technologically advanced economies covering the time span from 1980 to 2023. The econometric model is designed using the STIRPAT framework. The empirical results are based on panel time series analysis. The panel unit root tests illustrate that variables are stationary at the first difference and follow the I (1) order of integration. The panel cointegration test confirms the presence of long-run relationships between the variables. The empirical findings reveal that eco-digitalization, green technology, and green finance help to boost environmental sustainability by reducing carbon emissions and ecological footprints in technologically advanced economies. Furthermore, the empirical investigation proceeds using two major technological phases in the sampled economies. The results reveal heterogeneous effects of technological innovations and population growth on environmental quality across the phases of technological advancement. Our findings are helpful for policymakers, environmentalists, and development practitioners in designing and implementing policies that help mitigate carbon emissions and achieve environmental sustainability.

Keywords: Eco-digitalization, ICT, green technology, green finance, environmental sustainability, carbon emissions, ecological footprint.

1. Introduction

Countries all around the world are formulating and implementing policies to eliminate the adverse consequences of climate change. One of the major reasons behind climate change is the remarkable surge in the concentration of greenhouse gas (GHG) emissions. According to Global Carbon Budget (2024), world CO2 emissions have increased from 22.5 billion tons to 40.5 billion tons from 1980 to 2022. The rise in emissions is creating multi-dimensional challenges, such as changes in weather patterns, droughts, floods, and health issues (Zhang et al., 2021; Majeed & Ozturk, 2020). This situation is attracting the attention of policymakers, government, and research analysts to adopt such a productivity system, which brings improvement in the environment and promotes sustainability. Additionally, researchers and policymakers highlighted the need for environmental sustainability, for example, climate change, depletion of natural resources, environmental degradation, and food crises (Ones & Dilchert, 2012). Environmental sustainability can be achieved through various ways, such as reducing the use of fossil fuels, focusing on advanced recycling techniques, adopting renewable resources for energy generation, and bringing behavioral changes in day-to-day activities.

In this connection, every year, leaders from all over the world come together on the platform of the Conference of Parties (COP) to analyze the change in temperature level, to design policies for maintaining global average temperature, and to achieve environmental sustainability. COP-29 is the most recent gathering, and its main objectives are to enhance digital skills and climate finance for reducing CO2 emissions along with emphasizing the significance and need of energy transition. Furthermore, it has also reinforced the necessity and importance of environmental sustainability, which is the main agenda of COP-26 (Wei et al., 2025).

After COP-26 and COP-29, the research scholars are paying greater emphasis on exploring the diverse determinants of environmental sustainability (ES). In this respect, technological advancements, particularly in the form of eco-digitalization (EDIG), green technology (GTECH), and green finance (GFIN) are considering a significant attention from all over the world (Yang et al., 2022; Lin & Ma, 2022; Al Mamun et al., 2022; Ullah et al., 2021; Majeed, 2018). Digital technologies can exert diverse effects on ES (see, for details, Majeed, 2018). On the one hand, increasing digitalization helps to preserve the environment by improving energy efficiency, dematerialization effect, pollution control and reducing resource waste. On the other hand, these technologies can degrade the environment by increasing electronic waste, energy use, and resource extraction and exerting rebound effects.

Nevertheless, unlike digitalization, EDIG generally supports environmental preservation. According to the Organization for Economic Co-operation and Development (OECD, 2025), “eco-digitalization incorporates all economic activity reliant on, or significantly enhanced by the use of digital inputs, including digital technologies, digital infrastructures, digital services and data.” In effect, EDIG refers to the convergence of digital technologies and ecological sustainability.

EDIG has a significant influence on CO2 emissions mitigation. EDIG can optimize the process of economic activities by improving production efficiency. EDIG, in the shape of the IoT and advanced sensors, plays an effective role in lowering CO2 emissions and achieving energy efficiency (Bian et al., 2021). Additionally, EDIG is decreasing CO2 emissions through the introduction of electronic vehicles, such as electric cars.

GTECH is another important driver of ES. Green technological advancements can bring improvement in environmental quality by lowering emissions, preserving natural resources, and offering sustainable solutions such as energy-efficient systems and waste-reducing innovations. Cheng et al. (2021) argued that GTECH brings improvement in environmental quality by decreasing energy consumption and improving the procedure of production activities. Zeng et al. (2024) asserted that GTECH affects CO2 emissions by bringing changes to industrial and energy structures.

GFIN also plays a conducive role in ES. It helps to improve environmental quality by diverting financial resources to such activities that are not harmful to the environment (Fu et al., 2024). Muganyi et al. (2021) have identified three types of investment funds (green credit, green bonds, and carbon emissions trading) that have a substantial role in mitigating GHG emissions and bringing improvement in environmental quality. Meo & Karim (2022) have shown that GFIN has an effective positive role in attaining ES.

The present study investigates the effects of EDIG, GTECH, and GFIN on environmental quality in technologically advanced economies. These economies are early adopters of modern technologies. For instance, Hilty & Aebischer (2015) argued that these countries are adopting and supporting technological advancements in the shape of digitalization, green technology, and artificial intelligence for improving environmental quality. Besides, these economies have more authentic data banks on environmental indicators, energy efficiency, and green financing, allowing for more accurate empirical analysis (IEA, 2022).

Moreover, these economies possess a strong and effective system of environmental laws, carbon pricing, and financial benefits, which provides a logical foundation to analyze the effectiveness of green transitioning (OECD, 2021). The technical revolutions in these economies exert a significant influence on global sustainability trends through the transmission of technology, trading, and foreign direct investments (FDI). That is, green technologies are valuable to emerging economies (UNCTAD, 2022). Moreover, their advanced financial markets, which comprise green bonds and ESG (Environmental, Social, and Governance) plans, provide the required finance for developing green technology and fostering long-term environmental sustainability (OECD, 2021). Thus, studying technologically advanced nations offers important implications about the effectiveness, scalability, and future trajectory of EDIG and GFIN in driving sustainability worldwide.

This study contributes to existing literature through the following ways. First, we have investigated the effects of EDIG, GTECH, and GFIN on carbon emissions for technologically advanced countries over the period 1980 to 2023. Whereas most of the previous studies have investigated this nexus for China, European countries, and African countries. Second, unlike previous work (Umar & Safi,2023; Zeng et al., 2024) which mainly focused on CO2 emissions, this study also measured environmental quality using the ecological footprint, which represents a comprehensive measure of environmental quality. Third, unlike previous studies (Yang et al.,2022; Zhang et al., 2022) that have focused on the digitalization and environmental sustainability nexus, in this study, we analyzed the impact of eco-digitalization on environment sustainability. The study's findings are helpful for policymakers, environmentalists, and development practitioners in formulating and implementing policies that are not harmful to the environment and help achieve ES.

The remaining parts of the study are structured as follows: Section 2 reviews the existing literature, section 3 is about data description, model, and methodology, section 4 displays empirical findings, and lastly, section 5 concludes the study.

2. Literature Review

Environmental concerns have become a worldwide challenge owing to rising industrialization and the usage of fossil fuels. Therefore, initiatives to fight this threat are being implemented at both the national and international levels. In this regard, the role of technological advancements such as renewable energy, AI-driven technologies, and blockchain for carbon monitoring is important. The present study aims to analyze the role of technological advancement, such as eco-digitalization, green technology, and green finance on carbon emissions and ecological footprint. This part of the paper reviews the available literature and is divided into four sections.

2.1 Theoretical Underpinning

2.1.1 Theoretical Studies on Digitalization and Environment

Literature on the nexus of digitalization and environmental quality has emerged in recent years. However, the studies have identified diverse effects of digitalization on environmental quality. Recently, researchers have been paying attention to the environmentally conducive dimensions of digitalization, referred to as EDIG. In this context, digital twin theory is important. It allows work to transition from the physical world into the virtual world, creating main impacts on efficiency and effectiveness.

Network theory is also relevant in the context of EDIG and environmental preservation. Complex systems of interconnected digital technologies, environmental processes, and diverse stakeholders need high technical analysis and optimization. In this context, EDIG plays a key role in ensuring such optimization by mapping data flows and interdependent links, escalating collaboration among diverse green solutions, resource use efficiency, and supporting smart infrastructure such as Internet of Things (IoT)-enabled energy grids. The resulting networks support sustainable innovations and a smooth transition to a low-carbon and digitally integrated economy (Majeed & Ayub, 2018). The concept of circular economy is also relevant in shaping the links between EDIG and environmental sustainability. EDIG exploits digital technologies to implement circular economy practices such as product tracking, waste reduction, recycling, and predictive maintenance. It helps to attain close resource loops and sustainable consumption and production, thereby lowering emissions across industries.

The literature on the EDIG and environmental quality nexus is relatively scarce. The literature suggests that EDIG can influence carbon emissions through different ways such as the introduction of the IoT and advanced sensors which leads to energy efficiency (Bian et al., 2021). Besides, EDIG allows the simulation of eco-friendly interventions before implementation (Grieves, 2023). Additionally, the introduction of electronic vehicles which bring improvement and advancement in transportation (Yu & Liu, 2024) and through efficiency in the solar and wind energy management system. Besides, it allows the simulation of eco-friendly interventions before implementation (Grieves, 2023).

2.1.2 Theoretical Works on Green Technology and Environment

Additionally, green technology is an important tool for bringing improvement in environmental quality. The main objective of GTECH is to eliminate such activities that have awful consequences for the environment. It can eliminate CO2 emissions by reducing the ecological footprint of industries, infrastructure, and everyday life. Banerjee & Akuli (2014) asserted that adopting GTECH makes the process of evaluation, monitoring, and prevention more economical and efficient. Monitoring and evaluation technologies help in analyzing environmental conditions as well as measuring the release of harmful material from anthropogenic activities. Moreover, prevention expertise is adopted to decrease those production activities that harm the environment. Moreover, these technologies are adopted to improve ecosystems. Additionally, green technology helps mitigate GHG emissions via the deployment of renewable energy sources, improving resource efficiency and focusing on smart infrastructure (Nehra et al., 2023).

2.1.3 Theoretical Studies on Green Finance and Environment

Furthermore, green finance also has a substantial role in achieving environmental sustainability. GFIN refers to a sustainable financial system which promotes investment in renewable energy projects and discourages investment in such projects which lead to an incline GHG emissions (Wang & Zhi, 2016). Moreover, GFIN can play an effective role in reducing carbon emissions by providing investment in clean, more advanced, and less harmful production activities. Additionally, Wang & Zheng (2020) claimed that GIFAN promotes engagement of entrepreneurs in environmentally friendly production activities and it supports replacement of high energy equipment's with energy efficient products. Furthermore, Siedshlag & Yan (2020) have claimed that green finance brings improvement in firm performance indirectly positively contributing to environmental quality. Moreover, GFIAN can play an effective role in reducing carbon emissions by providing investment in clean, more advanced and less harmful production activities. Additionally, Xin et al. (2024) claimed that digital financial platforms and applications provide access to environmentally friendly products, for example green bonds.

2.2 Empirical Literature

2.2.1 Digitalization-Environmental Nexus

Various studies have empirically analyzed the association between digitalization and carbon emissions. For instance, Yang et al. (2022) found that a surge in regional digitalization brings a decline in carbon emissions intensity in China. Additionally, Wang et al. (2022a, 2022b) have examined this relationship for selected regions of China. By employing the Generalized Method of Moments (GMM), they demonstrated that digitalization helps in developing a low-carbon production system. Furthermore, digitalization has positive implications for acquiring technological advancement and sustainability. Additionally, Zhang et al. (2022) have studied this relationship for Chinese cities. The findings reveal that digitalization enhances the level of CO2 emissions, whereas energy efficiency plays a mediating role between digitalization and the environment. Moreover, Wang et al. (2022) have argued that the production activities of the digitalized industry have a crucial role in reducing CO2 emissions.

In addition, Skare et al. (2024) examined association among digitalization, carbon footprint, and sustainability for European Union countries. They found that digitalization has a progressive role in achieving sustainability. Moreover, digitalization also led to sustainability by decreasing carbon footprints. Furthermore, Bai et al. (2024) and Zhang et al. (2024) have provided evidence of an inverted U-shaped association between DIG and CO2 emission intensity. According to this, during the initial phases of digitalization, there is a rise in carbon emissions intensity, while at later stages, it brings a decline in carbon emissions intensity.

In contrast, another strand of literature has also highlighted the adverse impacts of digitalization on the environment. For example, Ahirwar & Tripathi (2021) and Dhir et al. (2021) have observed that digitalization can adversely influence the environment by producing e-waste in the development and manufacturing of electronic devices. The above discussion shows that previous studies have examined digitalization and environment sustainability nexus whereas analysis on eco-digitalization and ES is overlooked, particularly in the case of technologically advanced economies.

2.2.2 Green Technology-Environmental Nexus

Technology refers to the application of scientific knowledge to improve efficiency and advance innovation in products. Green technology, specifically, encompasses environmentally friendly technologies designed to reduce emissions, such as renewable energy and electric vehicles. Recently, empirical studies have investigated the role of GTECH in influencing CO2 emissions. Furthermore, Adebayo & Kirikkaleli (2021) have also studied the significant role of GTECH in eliminating CO2 emissions in Japan. Lin & Ma (2022) have explored the GTECH and CO2 emissions nexus for China. They claimed that GTECH has a heterogeneous effect on CO2 emissions across the cities of China. Moreover, GTECH can also mitigate CO2 emissions through upgrading industrial structures. In addition, Obobisa et al. (2022) have explored green innovation technology and carbon emission nexus for 25 African countries and finding indicates the positive impact of GTECH in eliminating CO2 emissions.

Moreover, Gao et al. (2022) have explored that GTECH can mitigate carbon emissions through bringing change and advancement in industrial structure. Additionally, they demonstrated that GTECH effects on CO2 emissions are not similar across different areas. Moreover, Husain et al. (2022) have explored this relationship for E7 countries. By applying second-generation estimation methodology, the study has proved that GTECH and renewable energy have a considerable contribution in attaining sustainability. Moreover, Anwar et al. (2022) have examined this relationship for 15 Asian countries for the time period 1990-2014 and demonstrated that green technology (renewable energy) brings a decline in carbon emission.

Guo et al. (2024) also examined the CO2 emissions effect of GTECH in the case of China. By doing spatial analysis, they found that green technological innovation can bring a notable reduction in carbon emissions at the provincial level in China. Additionally, Hu et al. (2024) have found that green and digital technology convergence has a considerable role in mitigating CO2 emissions in China. In addition, Zeng et al. (2024) have spatially analyzed this nexus for China. By employing the Spatial Durbin Model, this study explored that GTECH significantly mitigates local carbon emissions, whereas the spatial spillover effect of GTECH is not significant.

Furthermore, few studies have also found insignificant effects of GTECH on CO2 emissions reduction. For instance, Weina et al. (2016) claimed that GTECH has a significant role in improving environmental productivity, but it has an insignificant impact on carbon emission reduction. Above discussion suggests that previous studies have investigated this nexus for China, whereas analysis on technologically advanced countries is missing. Additionally, the past literature suggests mixed effects of green technologies on CO2 emissions.

2.2.3 Green Finance -Environment Nexus

Many studies have empirically analyzed green finance and the environmental nexus. For example, Shen et al. (2021) have examined this relationship for China for the time frame 1995-2017. Through CS-ARDL, their study explored that GFIN has a significant role in eliminating CO2 emissions in both the long run and short run, but the extent of the long-run impact is smaller than the short-run impact. Additionally, employing the ARDL (Auto Regressive Distributed Lag) model, Ibrahim et al. (2022) also found that GIFAN has a considerable role in creating a sustainable environment.

Additionally, Chin et al. (2022) explored that GFIN has a significant role in achieving environmental sustainability in Belt and Road Initiative (BRI) nations. Moreover, Meo & Karim (2022), by employing quantile-on-quantile regression, found a negative impact of green finance on carbon emissions in the United Kingdom, the USA, Hong Kong, Sweden, and Switzerland, whereas this impact was weak for Japan, Canada, Norway, Denmark, and New Zealand.

In addition, Umar & Safi (2023) investigated this relationship for OECD countries. By employing advanced econometric methodology, they found that GFIN can significantly lower CO2 emissions. Moreover, Udeagha & Ngepah (2023) have analyzed the impact of GFIN and financial technology on CO2 emissions for BRICS countries. The results demonstrated that GFIN has a substantial role in mitigating CO2 emissions in both the short and long run, and financial technology promotes environmental sustainability.

In a similar vein, Udeagha & Muchapondwa (2023) also explored how GFIN has a considerable role in promoting environmental sustainability. Fu et al. (2024) have empirically demonstrated that GFIN is crucial for decarbonization activities and bringing improvement in the environment. Additionally, Zaman et al. (2025) have investigated the green digital finance and environmental sustainability nexus for G-20. By employing the Method of Moments Quantile Regression (MMQR) they explored the positive impact of green technology finance on environmental sustainability. Similarly, Asif et al. (2025) have also analyzed this nexus for G-20 for a time period 2004-2023. They also explored the positive impact of green finance on environmental sustainability.

In contrast, Peng & Zheng ,(2021) have claimed that it promotes energy efficiency through the introduction of new technology whereas it hinders green innovation.

Most of the previous studies have examined the association between green finance and carbon emissions whereas analysis with ecological footprint is scarce. Additionally ,most of the previous studies while investigating this nexus have focused on green bonds (Siedschlag & Yan, 2029) and governmental green policy (Peng & Zheng,2021) but in this study we measured green finance with climate significant expenditure.

Most of the previous studies have examined the association between green finance and carbon emissions, whereas analysis with ecological footprints is scarce.

2.3 Summary, Gap, and Contribution to Literature

In sum, the studies on eco-digitalization, green technologies, and green finance have largely supported their environmentally sustainable impact by reducing carbon emissions. However, a few studies have also produced contradictory results demonstrating that these indicators disrupt environmental quality. The prior research has empirically examined this nexus for China, Europe, and Africa (Wang et al.,2022a; Obobisa et al.,2022; Chin et al., (2022). Further, most of these studies have employed traditional technological measures, with a focus on carbon emissions, ignoring the ecological footprint, which is a more advanced and broader indicator of environmental quality (Meo & Karim, 2022; Umar & Safi,2023; Zeng et al., 2024). A few research studies have employed advanced and comprehensive measures for single-country analyses. The literature on technologically advanced countries is overlooked.

The present study contributes to the literature in multiple ways. Firstly, it gives a comprehensive analysis of the effect of technological innovation on environmental sustainability by incorporating multiple indicators that measure technological advancements. Secondly, these measures are not general but specifically focused on the environment, including environment-related technologies, climate change mitigation in ICT, green finance, and renewable electricity net generation, ensuring a targeted assessment of sustainability-driven technological advancements to analyze their impact for the policy measures. Thirdly, this study incorporates two key environmental measures, carbon emissions and ecological footprints (number of Earths) to provide a comprehensive analysis. Since carbon footprints are a subset of ecological footprints, this procedure enables a more in-depth assessment of the environmental effect of technological advancements. Fourthly, the study analysis is done within the STIRPAT framework, which provides a holistic understanding of how technological advancements, economic growth, and policy measures interact to shape environmental sustainability. Fifthly, the study analyzes the association among the concerned variables for the technologically advanced countries over the period from 1980s to 2023. To our knowledge, past studies (Wang et al.,2022a; Obobisa et al., 2022; Chin et al., 2022) have overlooked this relationship in the case of technologically advanced economies. Sixthly, to capture the evolving relationship between technology and environmental sustainability, the present study divides the analysis into two phases. Phase I (1980–2009) examines how industrial expansion, digitalization, and early automation contributed to carbon emissions and ecological footprint. Phase II (2010–2023) explores the role of AI, eco-digitalization, and GFIN in mitigating climate change and promoting sustainability. This phased approach provides a comparative understanding of technological advancements in environmental sustainability. Lastly, the Fully Modified Ordinary Least Squares (FMOLS) method captures the long-run association between technological progress, economic affluence, and environmental sustainability. This approach provides robust insights into the extent to which eco-digitalization, green finance, and renewable energy contribute to reducing CO2 emissions and minimizing resource spending over time.

3. Data, Model and Methodology

This study intends to investigate the environmental effects of technological advancement through multiple dimensions, such as eco-digitalization, renewable energy, green finance, and renewable electricity generation. The sample is based on 19 technologically advanced countries. For empirical analysis, the sample size is decided depending upon data availability. The study analysis covers the period from 1980 to 2023. The data is collected from multiple secondary sources (details are available in Table 1). The empirical model is derived from the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) methodology developed by Dietz and Rosa (1997). This approach considers technology as an important factor of environmental sustainability, along with affluence and population. The STIRPAT model can be formally expressed as:

$$\mathbf{I = \alpha P^{b} A^{c} T^{d} e} \qquad \mathbf{eq.\,1}$$

Where the term I represents the environmental impact (measured through CO2 emissions and ecological footprint, P represents population (measured by the number of residents in a country, A affluence (measured through income per capita, and T technology (measured through eco-digitalization and technological innovation). α is the constant term, and b, c, and d are the exponential parameters for population, affluence, and technology, respectively. e is the error term capturing unexplained variability. Based on the available literature and particularly the study by Han et al. (2024), the empirical model for the study is expressed as:

$$\mathbf{LCO_{2\,i,t} = \beta_0 + \beta_1 LCO_{2\,i,t-1} + \beta_2 LEDIG_{i,t} + \beta_3 LGTECH_{i,t} + \beta_4 LGFIN_{i,t} + \beta_5 LREC_{i,t} + \beta_6 LGDPPC_{i,t} + \beta_7 LPOP_{i,t} + \mu_{i,t}} \qquad \mathbf{eq.\,2}$$

$$\mathbf{LEFP_{i,t} = \beta_0 + \beta_1 LEFP_{i,t-1} + \beta_2 LEDIG_{i,t} + \beta_3 LGTECH_{i,t} + \beta_4 LGFIN_{i,t} + \beta_5 LREC_{i,t} + \beta_6 LGDPPC_{i,t} + \beta_7 LPOP_{i,t} + \mu_{i,t}} \qquad \mathbf{eq.\,3}$$

CO_2 as carbon dioxide emissions (in eq.1) and EFP (in eq.2) as ecological footprint are the outcome variables representing environmental factors. The models are dynamic, and the lag of dependent variables is introduced in both equations. EDIG is the eco-digitalization, GTECH denotes green technology, GFIN denotes green finance, GDPPC is gross domestic product per capita, and POP is the population (a detailed description of the variables is in Table 1. All variables are transformed by taking the natural logarithm. The parameters such as β_0 is the constant, while all other parameters show the influence of related variables on the outcome variable. $\mu_{i,t}$ and $\varepsilon_{i,t}$ are error terms.

Table 1: Description of Variables

Variables	Synonyms	Measurement	Source
LCO2	Carbon Emissions	CO2 emissions in millions of metric tons (MMtonnes)	US-EIA (2025)
LEFP	Ecological Footprint	Number of earth (required to support human consumption)	GFN (2025)
LEDIG	Eco-Digitalization	Climate change mitigation in information and communication technologies (ICT)	OECD (2025)
LFTECH	Technological Innovation	Environment-related technologies (% of Inventions)	OECD (2025)
LGFIN	Green Finance (change mitigation)	Climate significant expenditure, (% of GDP	OECD (2025)
LREC	Renewable Energy	Renewable electricity net generation (billion kWh)	US-EIA (2025)
LGDPPC	Affluence	GDP per capita (constant 2015 US$)	World Bank (2025)
LPOP	Population	Population, total	World Bank (2025)

For empirical analysis, the study relies on panel cointegration techniques as checking the stationary property of the data is essential. For this the study utilizes the panel unit root such as Levin, Lin & Chu test by Levin et al. (2002), Breitung by Breitung (2001), Im, Pesaran, and Shin W-stat by Im et al. (2003), ADF-Fisher Chi-square and PP-Fisher Chi-square by Maddala & Wu (1999). Similarly, the Kao cointegration test by Kao (1999) and Pedroni cointegration test by Pedroni (1999) are applied to know the cointegration among the variables. Finally, FMOLS developed by Phillips and Hansen (1990) is utilized to provide long run estimates. It is a semi-parametric estimation technique designed to provide efficient and consistent estimates of long-run parameters in cointegrated systems. Unlike ordinary least squares (OLS), which can produce biased and inefficient estimates in the presence of endogeneity issues and serial correlation.

4. Empirical Findings

The empirical analysis has been done using EViews software. This section provides empirical findings and discussion.

4.1 Descriptive Statistics

Table 2 shows the summary statistics for the variables used in the study. According to the statistics, on average, technologically advanced countries are releasing carbon emissions of about 555.34 MM tonnes. The median value, 154.83, is significantly lower than the average value, showing that the countries have exceptionally high carbon emissions. The average value of the ecological footprint is 3.30543 number of earths, indicating that countries are using the earth's resources 3.30 times faster than the earth can regenerate them. The maximum value is 5.9435, which is greater than the mean value, reflecting the overconsumption and environmental strain.

On average, the eco-digitalization is 0.451008, showing the average level of climate change mitigation in ICT in the sample countries. The maximum value is 2.66794, while the lowest score is 0.005749, showing that the sample economies vary from the mean due to differences in ICT, particularly in terms of climate change mitigation. Further, on average, environmental-related technological innovation from the overall innovations in the sample countries is 7.782725, while the maximum value is 50.9615, indicating a high level of environmental-related technological innovation in the sample economies. The countries, on average, spend 227.9419 on climate change mitigation. Further, the average net generation of renewable energy kWh is 75.23853, with a wide range from 0.2 to 979.

Table 2: Descriptive Statistics

	Obs.	Mean	Median	Max.	Min.	Std. Dev.
CO2	750	555.341	154.83	6015.7	19.743	1203.12
EFP	718	3.30543	3.1782	5.9435	1.5382	0.8395
EDIG	525	0.451008	0.298332	2.66794	0.005749	0.455979
GTECH	605	7.782725	1.54316	50.9615	0.040698	10.34953
CFIAN	328	227.9419	50.232	1321.98	0.349	313.44
REC	737	75.23853	39	979	0.2	117.72
GDPPC	826	39427.57	36207.1	99677.5	10475.1	15787.44
POP	836	43234928	11000000	3.30E+08	3400000	66000589

4.2. Correlational Analysis

Table 3 provides the statistics of correlation analysis. The findings suggest a strong correlation between population with carbon emissions and medium with the ecological footprint. Further, the net generation of renewable electricity has a medium correlation with CO_2 emissions and ecological footprint. All the other variables, such as green technology, climate finance, and GDP, have a low correlation with both environmental indicators.

Table 3: Correlation Matrix

Variable	CO2	EFP	EDIG	GTECH	CF	REC	GDPC	POP
CO2	1							
EFP	-0.423	1						
EDIG	-0.177	0.034	1					
GTECH	-0.128	-0.075	-0.173	1				
CF	0.325	-0.109	0.044	0.010	1			
REC	0.466	-0.466	-0.050	-0.213	-0.088	1		
GDPC	-0.367	0.060	0.057	0.365	-0.159	0.102	1	
POP	0.964	-0.544	-0.183	-0.184	0.339	0.538	-0.399	1

4.3. Results of Unit Root Test

Unit root tests such as Levin, Lin & Chu, Breitung, Im, Pesaran, and Shin W-stat, ADF-Fisher Chi-square, and PP-Fisher Chi-square are used to analyze the variable series to check their stationary property. The results of the unit root test at the level are reported in Table 4. The results indicate that all of the variables are non-stationary at the level, since the probability value is larger than the significance level ($p>0.1$), supporting the null hypothesis.

Table 4: Unit Root Test (At Level)

	Null Hypothesis (Ho): Unit Root Exists (Non-Stationary Series)				
	Assumes common unit root process		Assumes individual unit root process		
	Levin, Lin & Chu	Breitung	Im, Pesaran and Shin W-stat	ADF - Fisher Chi-square	PP - Fisher Chi-square
LCO2	0.7143	2.7913	3.7115	18.154	18.501
	(0.762)	(0.997)	(0.999)	(0.994)	(0.993)
LEFP	-0.9767	0.4071	1.2170	36.8344	38.0127
	(0.1644)	(0.658)	(0.8882)	(0.3391)	(0.2915)
LEDIG	15.0047	5.8485	2.9268	15.005	343.20
	(1.000)	(1.000)	(0.998)	(0.999)	(0.000)
LGTECH	8.1015	7.0988	3.0622	32.0384	314.64
	(1.000)	(1.000)	0.9989	(0.7408)	(0.000)
LCF	8.7140	-2.7121	-0.5852	37.7891	754.30
	(1.000)	(0.0033)	(0.2792)	(0.3875)	(0.000)
LREC	2.4936	2.5430	-0.3015	45.2834	147.31
	(0.993)	(0.994)	(0.381)	(0.138)	(0.000)
LGDPC	-0.8426	3.1638	3.2746	17.5063	16.843
	(0.200)	(0.999)	(1.000)	(0.998)	(0.999)
LPOP	1.2860	19.9604	7.1748	9.3398	9.7494
	(0.900)	(1.000)	(1.000)	(1.000)	(1.000)

Table 5 shows the results of the unit root test at first difference. The data reveal that all of the series probability values are less than the significant threshold, supporting the rejection of the null hypothesis. As a result, the alternative hypothesis of no unit root is accepted, suggesting that the series has become stationary after the first difference.

Table 5: Unit Root Test (At First Difference)

	H_1: No Unit Root (Stationary Series)				
	Assumes common unit root process		**Assumes individual unit root process**		
	Levin, Lin & Chu	**Breitung**	**Im, Pesaran and Shin W-stat**	**ADF - Fisher Chi-square**	**PP - Fisher Chi-square**
LCO2	-28.635	-11.584	-27.431	538.67	1120.99
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LEFP	-26.886	-16.034	-26.237	546.08	1441.34
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LEDIG	-31.984	-3.896	-27.948	668.40	1570.82
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LGTECH	-16.000	-0.2810	-19.782	417.37	507.37
	(0.000)	(0.389)	(0.000)	(0.000)	(0.000)
LCF	-32.991	-0.2954	-31.8685	1260.72	1113.3
	(0.000)	(0.383)	(0.000)	(0.000)	(0.000)
LREC	-26.392	-9.151	-28.586	613.072	1870.240
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LGDPC	-21.959	-11.143	-18.467	330.893	600.741
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
LPOP	-2.769	-0.907	-5.216	94.551	60.342
	(0.002)	(0.182)	(0.000)	(0.000)	(0.012)

4.4. Results of the Cointegration Test

Table 6 reports the results of the cointegration test. The findings of Kao and Pedroni's cointegration test suggest that cointegration exists between the variables as the probability values are less than the significance level ($p<0.1$). Therefore, there is a need to estimate the long-term coefficients.

Table 6: Results of the Cointegration Test

Kao Residual Test for Cointegration Test				
	Model 1		**Model 2**	
Test Statistics	2.4552		1.8849	
Probability	(0.007)		(0.029)	
Pedroni Cointegration Test				
H_1: Common AR Coefficients (within-dimension)				
	Model 1		**Model 2**	
Tests	**Statistic**	**Weighted Statistic**		
Panel v-Statistic	-0.5613	-0.7255	-0.1836	-0.7810
	(0.712)	(0.766)	(0.572)	(0.782)
Panel rho-Statistic	-1.3152	-0.9330	-1.7507	-0.0262
	(0.094)	(0.175)	(0.040)	(0.489)
Panel PP-Statistic	-6.2435	-5.7340	-8.0853	-4.5109
	(0.000)	(0.000)	(0.000)	(0.000)
Panel ADF-Statistic	-4.7147	-3.8452	-8.4582	-4.4631
	(0.000)	(0.000)	(0.000)	(0.000)
H_1: Individual AR Coefficients (between-dimension)				
Tests	**Model 1**		**Model 2**	
Group rho-Statistic	0.5363		0.4001	
	(0.704)		(0.655)	
Group PP-Statistic	-6.6351		-6.851	
	(0.000)		(0.000)	
Group ADF-Statistic	-4.8723		-6.652	
	(0.000)		(0.000)	

4.5. Results of FMOLS

The results of FMOLS are shown in Table 7. The results indicate that the lag value of both carbon emissions and ecological footprints are positive and significant, indicating that the previous year's level of these indicators increases environmental unsustainability by enhancing their levels. This is because these emissions remain in the environment over time, causing further environmental degradation. Similarly, the other sources such as land degradation and deforestation take longer to recover. This finding is consistent with Wackernagel & Lin (2023).

Further, EDIG plays a significant role in preserving the environment. The coefficient on EDIG indicates that a 1 percent rise in it leads to a 0.008 and 0.004 percent fall in carbon emissions and ecological footprint, respectively. This is because ICT-related technologies such as AI and the IoT, through the availability of smart technologies such as smartwatches, connected cars, cities, security systems, and healthcare monitors help to increase energy efficiency, track emissions concentrations in the environment, and provide safer options. Therefore, these technologies help to support the ES in the sampled economies. Similar results are reported by Belkhir & Elmeligi (2018) and Han et al. (2024).

Further, green technology innovations like LED lighting, plant-based packaging, recycling, waste management, rain harvesting, sustainable agriculture, and others also help to bring down carbon emissions and ecological footprints in the countries by 0.005 and 0.004 percent by providing precision technologies benefits and resource-saving. The coefficient of green finance is significant and carries a negative sign. Funding for the environment is crucial since it provides the resources to invest in green technologies and makes it feasible for the public and companies to make innovations and then transit themselves towards updated efficient technologies. Therefore, green finance through investment in green bonds, eco-efficient technologies and promoting circular economy assist the technologically developed counties in achieving sustainability targets. These findings are similar to the findings of Johnson & Swem (2021) and Han et al. (2024).

Additionally, a 1 percent rise in renewable electricity is linked with a 0.0202 and 0.0079 percent fall in CO_2 emissions and ecological footprint, respectively. Similar findings are obtained by Jacobson et al. (2015) and Han et al. (2024). According to them, electricity generated through renewable energy sources is clean and power-efficient compared to traditional fossil-fuel-based power. Economic growth is considered important for the environment as economic activities are highly linked with greater pollution and natural resource utilization. According to the findings in Table 7, income per capita is linked with a rise in carbon emissions and the ecological footprint. This finding can be aligned with the concept of Scale Effect, which supports the positive relationship between increasing economic activities (owing to increased income) and carbon emissions (Majeed & Tauqir, 2020). These findings are supported by Majeed & Mazhar (2019) and Mohamed et al. (2024). Lastly, the relationship between population and environmental sustainability seems to be surprising, which may be due to the higher population concentrated in the areas with lower environmental issues. Further, this also indicates that technologically developed countries' populations are well aware of environmental protection and behave accordingly. The important aspect in this regard can be that environmental laws are strict and executed, making higher population less harmful for the environment. The R-square is higher, indicating that models are a good fit and independent variables well explain the dependent variables.

Table 7: Results from FMOLS

	Dependent Variable	
	CO_2 Emissions	**Ecological Footprint**
Environment $_{t-1}$	0.8801***	0.8832***
	(0.0021)	(0.0026)
EDIG	-0.0081***	-0.0044***
	(0.0003)	(0.0003)
GTECH	-0.0054***	-0.0047***
	(0.0005)	(0.0002)
CFIAN	-0.0012***	-0.0015***
	(0.0003)	(0.0001)
REC	-0.0202***	-0.0079***
	(0.0005)	(0.0003)
GDPPC	0.1036***	0.0204***
	(0.0022)	(0.0005)
POP	-0.1419***	-0.0027***
	(0.0022)	(0.0002)
R-Squared	0.9983	0.8499

4.5. Sensitivity Analysis and Robustness Check of FMOLS Findings

To check the reliability and consistency of the empirical findings, we have repeated our analysis by splitting the data into two phases based on technological innovations in the sample economies. The first phase consists of the expansion of digitalization and industrial automation. The period of this industry and digital revolution spans from the 1980 to 2009 in which hardware-driven sectors such as automotive, telecommunications, manufacturing, and early computers witnessed substantial transformations. The emergence of personal computers and the internet boom drove enormous transformations in industry and society, marking the beginnings of the digital revolution (Frey & Osborne, 2017; Wang et al. 2024).

Table 8 reports these findings, which are broadly similar to earlier empirical findings, suggesting that results are not substantially sensitive. The results indicate two exceptions, first, the influence of technological advancement varies from positive to negative across two phases. Second, similarly, the influence of population growth varies from positive to negative between these phases. These findings are justifiable as the early years of technological innovations such as personal computers, mobile technologies, and industrial robots boosted energy consumption and electronic waste creation, escalating carbon emissions (Frey & Osborne, 2017; Chen & Zhou, 2024). In contrast, the negative relationship between technological innovations and environmental indicators is consistent with the previous findings. These findings highlight the positive role of technological advancement in the sample economies as automation and digital control systems increased energy efficiency in areas including manufacturing and transportation, eliminating waste and maximizing resource use (IEA, 2009; Song et al. 2024; Zaghdoud, 2025).

Table 8: Phase (I) Industrial and Digital Transformation (1980-2009)

	Dependent Variable	
	CO_2 Emissions	**Ecological Footprint**
Environment $_{t-1}$	0.7092^{***}	0.8045^{***}
	(0.0161)	(0.0022)
EDIG	-0.0032^{**}	0.0006^{**}
	(0.0016)	(0.0003)
GTECH	0.0245^{***}	-0.0003^{***}
	(0.0030)	(0.0001)
CFIAN	-0.0121^{***}	-0.0048^{***}
	(0.0018)	(0.0002)
REC	-0.0414^{***}	-0.0134^{***}
	(0.0035)	(0.0003)
GDPPC	0.0860^{***}	0.0324^{***}
	(0.0167)	(0.0003)
POP	0.0277^{***}	-0.0034^{**}
	(0.0438)	(0.0002)
R-Squared	0.9989	0.81010

Table 9 shows the findings for the current era, which is dominated by AI, quantum computing, and sustainability. Today, AI has become the foundation of several businesses, including fintech, cybersecurity, biotechnology, and space exploration (Russell and Norvig, 2016). Companies such as Google, IBM, and OpenAI have spearheaded AI research, pushing progress in machine learning, deep learning, and AI-powered automation. Another key development has been an emphasis on sustainability and renewable energy. Governments and companies throughout the world, particularly technologically advanced countries, have made significant investments in renewable energy sources such as solar, wind, and hydrogen power, with the goal of achieving carbon neutrality in the future. Countries like Sweden, Norway, and Germany have emerged as pioneers in green technology and electric vehicle adoption, with businesses like Tesla and

BMW pushing automotive innovation (Amri & Nasri, 2025). The empirical findings support the positive effect of technological innovations in fighting environmental degradation. The findings in Table 9 are consistent with earlier findings, supporting the reliability of the results.

Table 9: Phase-The Era of AI and Sustainability (2010-2023)

	Dependent Variable	
	CO_2 Emissions	**Ecological Footprint**
Environment $_{t-1}$	0.8035^{***}	0.9743^{***}
	(0.0016)	(0.0009)
EDIG	-0.0075^{***}	-0.0050^{***}
	(0.0002)	(0.0002)
GTECH	-0.0151^{***}	-0.0014^{***}
	(0.0001)	(0.0001)
CFIAN	-0.0007^{***}	-0.0028^{***}
	(0.0002)	(0.0001)
REC	-0.0407^{***}	-0.0018^{***}
	(0.0006)	(0.0002)
GDPPC	0.1272^{***}	0.0064^{***}
	(0.0026)	(0.0004)
POP	0.1088^{***}	-0.0022^{***}
	(0.0064)	(0.0003)
R-Squared	0.9983	0.9216

5. Conclusion

This study explores the effects of EDIG, GTECH, and GFIN on environmental sustainability for technologically advanced countries over the period 1980-2023. The outcome variable is environment sustainability measured through CO2 emissions and ecological footprint, while the focus variables are eco-digitalization, green technology, and green finance. The empirical analysis has been done through FMOL. Unlike OLS, which can produce biased and inefficient estimates in the presence of endogeneity and serial correlation, FMOLS modifies the OLS estimator to overcome these issues. The results of FMOLS demonstrate that all the variables concerned have a significant and effective role in achieving ES, as all the variables' coefficients carry negative signs. Further, the results for different phases of technological advancement are consistent with these findings.

5.1 Contribution of the Study

This study contributes to existing literature in the following ways. First, we have investigated the relationship among EDIG, GFIN, GTECH, and carbon emissions for technologically advanced countries over the period 1980 to 2023. Second, unlike previous work, which mostly focused on CO2 emissions, this study also measured the environment with the ecological footprint, which represents environmental quality comprehensively. Third, this study extends the debate by considering urbanization and affluence in the STIRPAT framework. Last, the study's findings are helpful for policymakers, environmentalists, and development practitioners in formulating and implementing policies that are not harmful to the environment and helpful in achieving environmental sustainability.

5.2 Policy Implications

The empirical outcomes of the present study offer the following policy implications. The significant effective role of EDIG in reducing CO2 emissions and ecological footprint illustrates that the governments of technologically advanced countries need to enhance the level of investment in enhancing digital technologies, which in turn help achieve ES. The substantial contribution of green technology in attaining environmental sustainability also emphasizes that the advancement of GTECH is essential for bringing improvement in environmental quality. Governments need to incentivize green technology adoption through tax breaks, subsidies, and research funds. Besides, technological transfer development economies need to be accelerated through international agreements. GFIN has a significant influence on carbon emissions reduction, which implies that the governments of technologically advanced countries need to formulate policies for promoting green finance. In this regard, governments need to develop green bond markets and partner with banks to fund renewable energy, green technology, and climate-resilient infrastructure.

5.3 Limitations of the Study

This study has certain limitations. First, the sample size is limited to a panel of 19 countries due to the unavailability of data. Second, the study mainly focused on the panel of technologically advanced economies, whereas the country-specific analysis of selected economies can offer more comprehensive and comparable analysis. Third, the present study did not consider the interactive effects of GFIN with EDIG and GTECH.

5.4 Future Research Directions

Future studies can further elaborate on this study by conducting a comparative analysis of developed and developing countries. Besides, a country-specific analysis can be provided to tailor the policies in line with the needs of an individual country. Furthermore, future studies can explore the interactive effects of GFIN with EDIG and GTECH.

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