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# GREEN TECHNOLOGY INNOVATION, GREEN FINANCING, AND ECONOMIC GROWTH IN G7 COUNTRIES: IMPLICATIONS FOR ENVIRONMENTAL SUSTAINABILITY

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## ABSTRACT

This study examines the relationships among green technology innovation, green financing, economic growth, and environmental sustainability in G7 countries using annual data from 1990 to 2022. It uses the cross-sectionally augmented autoregressive distributed lag model to estimate environmental sustainability through two indicators: ecological footprint and carbon dioxide (CO2) emissions. The CO2 emissions model indicates that green financing negatively affects emissions, highlighting the need to reduce them and promote sustainable practices. Conversely, energy consumption and real GDP per capita (RGDP) positively impact CO2 emissions. Green technology innovation also reduces CO2 emissions, but its short-term effects may be limited owing to initial energy consumption and regulatory challenges. The ecological footprint model demonstrates that, in the long term, green technology innovation helps lower the ecological footprints of G7 countries by promoting infrastructure development and reducing resource consumption. However, short-term constraints and high initial costs hinder this progress. Green financing is essential for achieving long-term sustainability. Energy consumption positively influences the ecological footprint, while short-term RGDP growth increases it. However, long-term RGDP may decline owing to sustainability policies, technological advancements, and effective environmental legislation. These findings underscore the importance of balanced policies that prioritise green finance in the short-term to mitigate environmental impacts while fostering long-term investments in green technology innovation. Additionally, enhancing international cooperation and aligning investments with green objectives are crucial for achieving sustainable prosperity and minimising environmental harm.

***Keywords:*** *Carbon dioxide (CO2) emissions, RGDP, Ecological Footprints, CS-ARDL, Energy Consumption*

## 1. INTRODUCTION

Climate change poses a significant threat to ecosystems and civilisation (Triki et al., 2023). The first global initiative aimed at reducing environmental pollution was the Kyoto Protocol, established in 1997. This protocol seeks to combat climate change by decreasing worldwide carbon dioxide (CO2) emissions (Pata & Caglar, 2021). In 2015, the Paris Climate Agreement was finalised, recognising climate change as a pressing environmental and societal threat (Ude-

agha & Muchapondwa, 2023). The Paris Agreement primarily aims to achieve net-zero global emissions and limit the increase in global temperatures to below 2°C, that is, above pre-industrial levels, while aiming to further reduce it to 1.5°C (Ibrahim et al., 2023). In November 2021, the United Nations Climate Change Conference (COP26) highlighted concerns about fossil fuel-dependent nations, which have historically prioritised economic gains over negative environmental impacts. Concerns about the continuous increase in CO2 emissions were also highlighted (Udeagha & Breitenbach, 2023). Grossman (1995) noted that economic growth requires more resources and industries to boost production, leading to increased waste, pollution, and environmental degradation, as described by the environmental Kuznets curve (EKC). Replacing outdated technologies with modern, eco-friendly alternatives is an effective strategy to maintain the current economic landscape while reducing pollution (Triki et al., 2023). However, Zafar et al. (2021) found that technological innovation can sometimes diminish environmental sustainability. In response, governments have promoted sustainable energy sources and green finance to mitigate these negative impacts (Maliat et al., 2024). According to the United Nations Framework Convention on Climate Change (UNFCCC) (2021), finance and technology are crucial in reducing greenhouse gas emissions by up to 40% by 2030 (Jian & Afshan, 2023).

The ecological footprint, CO2 emissions, and their connection to climate change are significant global issues (Bilgili & Ulucak, 2018). The ecological footprint, widely used to assess sustainability, measures anthropogenic environmental pressure by evaluating resource use, lifestyles, goods, services, firms, cities, towns, regions, and countries (Solarin et al., 2019). Nathaniel (2021) highlighted its significance as an indicator of the environmental impacts of energy and production processes.

Green finance is an emerging trend that integrates finance and business with environmentally friendly practices. It emphasises environmental benefits, particularly within the environmental protection industry (Wang & Zhi, 2016). According to Salazar (1998), green finance is a financial innovation designed to meet environmental protection needs. It aims to fund sustainable initiatives, with ecological security as a primary driver. On June 4, 2003, the world's top 10 banks signed the 'Equator Principles' in London, establishing voluntary guidelines to address financial concerns related to social and environmental impacts (Mngumi et al., 2022). These principles aim to minimise environmental damage across various sectors, including energy, health, and wealth (Ye et al., 2022). Green finance involves private companies funding environmentally friendly initiatives that contribute to promoting sustainable growth (Li & Deng, 2024). These investments help improve ecological integrity, support the creation of environmentally sustainable industries, and enhance the development of credit intermediaries backed by the global financial community (Gajović, 2024). Green bonds, CO2 emissions trading, and green credit are the primary eco-friendly investment products (Muganyi et al., 2021). According to Al Mamun et al. (2022), green finance is a valuable tool for achieving global carbon-neutrality targets by increasing investments in green projects, green bonds, and climate mitigation efforts. Several studies have demonstrated that green finance positively impacts environmental sustainability (Rasoulinezhad & Taghizadeh-Hesary, 2022; Sampene et al., 2022; Shan et al., 2021; Udeagha & Muchapondwa, 2023; W. Wu et al., 2021; Xia et al., 2023).

Green technology innovations are crucial in both environmental protection and economic development. Technological advancements help focus on long-term development goals, such as environmental sustainability and carbon neutrality (Shan et al., 2021). Braun and Wield (1994) defined green technology as encompassing pollution management, ecological treatment, purification, recycling, monitoring, and other evaluation methodologies. Green technology, also referred to as eco-innovation, focuses on environmental considerations by improving products, services, and processes while progressively reducing net environmental impacts (Berkel, 2007). Xu et

al. (2023) noted that green technology enhances energy efficiency, promotes renewable energy, and reduces carbon emissions. Feng et al. (2009), Huang et al. (2021), and Temesgen Hordofa et al.(2023) showed that green technology innovation significantly decreases CO2 emissions.

Several studies have explored the relationship between economic growth and CO2 emissions, yielding mixed results. Some research indicates that economic growth increases carbon emissions and ecological footprints (Acheampong, 2018; Ahmed, Ahmad, Rjoub et al., 2022; Akram et al., 2020; Danish et al., 2019), while other studies report the opposite (Akbostancı et al., 2009; Mrabet et al., 2017).

G7 countries, which account for approximately 46% of global GDP (Ahmed, Ahmad, Murshed et al., 2022) and over 60% of the world's net wealth (Alola et al., 2022), are major contributors to CO2 emissions. These countries consume nearly one-third of the world's energy annually and contribute approximately a quarter of global greenhouse gas emissions, making the transition to renewable energy crucial for reducing CO2 emissions (Gessinger, 1997).

No prior studies have used both CO2 emissions and ecological footprint as indicators of environmental sustainability. To address this gap, this study explores the nexus between green technology innovation, green financing, economic growth, and environmental sustainability.

This study makes several contributions to the existing literature. To the best of my knowledge, only one prior study has focused on G7 countries using CO2 emissions as a proxy for environmental sustainability. Unlike Sharif et al.'s (2022) study, which measured environmental sustainability solely through CO2 emissions, this study uses both CO2 emissions and ecological footprint. Given the significant role of G7 countries in global economic diversification, accounting for 25% of the world's CO2 emissions and approximately 30% of its overall energy demand (Liu et al., 2023), this study provides critical insights into sustainable development, thereby enriching the body of research on G7 countries. The following research questions are posed:

Does green technology innovation significantly reduce CO2 emissions?

Does green financing significantly reduce CO2 emissions?

Does economic growth significantly increase CO2 emissions?

Does green technology innovation significantly reduce the ecological footprint?

Does green financing significantly reduce the ecological footprint?

Does economic growth significantly increase the ecological footprint?

The remainder of this paper is organised as follows: Section 2 reviews the relevant literature and identifies gaps; Section 3 presents the theoretical framework, data, and methodology; Section 4 discusses the empirical results; and Section 5 concludes with policy recommendations and limitations.

## 2. LITERATURE REVIEW

CO2 is one of the most harmful environmental pollutants, disrupting weather patterns and degrading natural resources. Reducing CO2 emissions is essential to ensure a clean and healthy environment. Green financing and green technology innovation are effective strategies for this reduction, as they enhance the efficiency of business resources and processes while decreasing CO2 emissions (Sadiq et al., 2024). This study assesses environmental sustainability using two key measures: CO2 emissions and ecological footprint.

## 2. 1. GREEN TECHNOLOGY INNOVATION, GREEN FINANCING, ECONOMIC GROWTH, AND ENVIRONMENTAL SUSTAINABILITY

Ibrahim et al. (2023) used annual data from 1995 to 2019 for the ten top natural-resource-dependent countries. They employed cross-sectionally augmented autoregressive distributed (CS-ARDL), common correlated mean effects (CCEMG), augmented mean group (AMG), and novel quantile regression to estimate their model. Their findings indicated that renewable energy, structural change, green finance, and technological advancement helped these countries avoid further environmental damage. Saqib et al. (2024) studied ten countries with the largest ecological footprints from 1990 to 2019 using the CS-ARDL approach. They found that environmental innovations, renewable energy, and green growth improved the environment, while financial expansion and non-renewable energy had negative effects. A bidirectional causal relationship existed between these factors. Feng (2022) employed fully modified ordinary least squares (FMOLS) and a Markov switching regression model to examine data from 1998 to 2018 in China. The results showed that green finance, green energy, openness, and R&D expenditures significantly contribute to environmental quality. Jian and Afshan (2023) examined the impact of green financing and technologies on carbon neutrality from 2000 to 2018 in G10 economies, using a panel ARDL approach. They demonstrated that green finance and technology support carbon neutrality in both the long and short terms (Wang et al., 2024). Sharif et al. (2022) explored the relationship between green technology innovation, green financing, and sustainable environments in G7 countries from 1995 to 2019. Using a CS-ARDL approach, they found that green technology innovation and financing negatively and statistically significantly explained CO2 emissions, while economic growth significantly and positively influenced emissions. Triki et al. (2023) estimated the effects of renewable energy, green finance, and public health expenditures on environmental quality in Saudi Arabia from 1980 to 2020. They used ARDL and nonlinear ARDL (NARDL) approaches. The ARDL results indicated that all variables contributed to improved environmental quality in the long run. The NARDL approach also highlighted asymmetric shocks, demonstrating an unbalanced relationship with variable movements over the short and long term. Finally, Zhang et al. (2022) investigated the dynamic relationships among renewable energy consumption, environmental pollution, and climate change for 49 countries from 2007 to 2019 using a system generalised method of moments (GMM) estimation. They found bidirectional relationships among these factors. Innovation increased renewable energy consumption, reduced CO2 emissions, and mitigated climate change (Puška et al., 2023). Notably, innovation had a greater negative impact on CO2 emissions and a diminishing effect on climate change when green financing development was high.

## 2. 2. GREEN TECHNOLOGY INNOVATION, AND ENVIRONMENTAL SUSTAINABILITY

Huang et al. (2021) examined the effects of green investment, renewable energy consumption, and technological innovation on CO2 emissions across 30 Chinese provinces from 1995 to 2019, using the CS-ARDL approach. Their results indicated that renewable energy, technological innovation, and green investment significantly decreased CO2 emissions. Temesgen Hordofa et al. (2023) investigated the impacts of eco-innovation and green investment on CO2 emissions, utilising Chinese data from 1990 to 2019 and adopting the ARDL approach. They found that both eco-innovation and green investment contributed to reductions in CO2 emissions, suggesting the need for stronger environmentally friendly policies and increased green investments to mitigate emissions. Feng et al. (2009) examined the relationships among urbanisation, technological innovation, income levels, and carbon emissions in China during the same period. Their findings revealed that technological innovation, rapid urbanisation, and per capita

income significantly impact environmental emissions.

## 2. 3. GREEN FINANCING AND ENVIRONMENTAL SUSTAINABILITY

X. Wu et al. (2021) employed FMOLS and robust vector error correction model techniques to estimate a long-run model using annual data from 2010 to 2018 for E7 and G7 countries. They found that climate change mitigation indicators have a stronger impact on G7 countries' GDP than E7 countries. Additionally, green funding strategies assist in environmental clean-up and boost policymakers' confidence in promoting green economic growth in both G7 and E7 countries. The green financing index also improves environmental quality in these regions. Yang et al. (2022) analysed G7 economies from 2010 to 2018, discovering that clean energy, green financing, and green economic development are significant indicators of cumulative sustainable practices. Rasoulinezhad and Taghizadeh-Hesary (2022) used GMM to examine data from the top ten economies between 2002 and 2018. Their findings demonstrate that green bonds effectively encourage green energy projects and significantly reduce CO2 emissions. Sampene et al. (2022) analysed annual data for South Asia from 1990 to 2017 using a CS-ARDL approach. Their results indicate that the use of renewable energy, green finance, and information and communication technology mitigated the ecological footprint. Udeagha and Muchapondwa (2023) applied CS-ARDL to estimate a model for the BRICS region between 1990 and 2020, finding that green finance, fintech, and energy innovation support environmental sustainability. Shan et al. (2021) applied the bootstrapping ARDL-bound testing technique to analyse data from Turkey spanning 1990 to 2018. Their findings indicate that green technology innovation and renewable energy contribute to reducing CO2 emissions, while energy consumption, population growth, and per capita emissions drive increases. Saeed Meo and Karim (2022) utilised quantile-on-quantile regression to examine monthly data from November 2008 to June 2019 across the ten leading economies in green finance. Their study confirmed that green finance significantly reduces CO2 emissions, identifying it as the most effective financial strategy for this purpose. Similarly, Gong et al. (2024) employed a quantile-on-quantile approach to investigate data from January 2007 to December 2020 in the BRICS+6 economies. Their results demonstrate that green finance enhances environmental quality by reducing the carbon footprint across various quantiles of the data distribution.

## 2. 4. ECONOMIC GROWTH AND ENVIRONMENTAL SUSTAINABILITY

Acheampong (2018) used panel vector autoregression and GMM to analyse data from 116 countries between 1990 and 2014. The study found that while economic growth reduces carbon emissions, carbon emissions still have a positive effect on economic growth. Ahmed, Ahmad, Rjoub, et al. (2022) utilised continuously updated, fully modified techniques to estimate data for G7 countries from 1985 to 2017. Their findings indicate that economic growth enhances the ecological footprint. Danish et al. (2019) employed the ARDL method to examine the relationship between GDP and environmental quality in BRICS countries from 1971 to 2014. They found that economic growth increases environmental degradation. Akram et al. (2020) reported that GDP increased emissions in 66 developing countries from 1990 to 2014, with the strongest mitigation effects observed in the upper quantiles, thereby confirming the existence of the EKC hypothesis. Conversely, Mrabet et al. (2017) used the ARDL model to analyse data from Qatar for the period 1980 to 2011. They found that income has a greater long-term effect than a short-term effect, indicating a monotonic relationship between the ecological footprint and real GDP. Akbostancı et al. (2009) applied cointegration techniques to Turkish data from 1992 to 2001, showing a monotonically increasing relationship between CO2 emissions and income in the long run. However, they found an N-shaped relationship for CO2 emissions, contradicting

the EKC hypothesis, which assumes an inverted U-shaped relationship. Alvarado et al. (2024) employed second-generation cointegration quantile regression models to study 88 economies from 1996 to 2021. Their findings suggest that technology is more associated with maximising production than with mitigating or restoring environmental deterioration.

### 2. 5. SUMMARY OF LITERATURE GAPS AND THE STUDY'S CONTRIBUTIONS

This study differentiates itself from previous research by focusing on G7 countries and examining the impacts of green technology innovation, green financing, and economic growth on environmental sustainability. Notably, no prior studies have used both CO2 emissions and ecological footprint as indicators of environmental sustainability in this context. This study is based on the stochastic impacts by regression on population, affluence, and technology (STIRPAT) model, where green finance is measured by the budget allocated to renewable energy public research, development, and demonstration (RD&D). It identifies a gap in the literature, as no studies have utilised this specific scale, and aims to fill that gap.

## 3. THEORETICAL FRAMEWORK, DATA, AND METHODOLOGY

### 3. 1. THEORETICAL FRAMEWORK

The theoretical framework for this study is based on the STIRPAT model. STIRPAT is an evolution of the IPAT and ImPACT models, which are closely related (York et al., 2003). The IPAT model represents environmental impacts (I) as a function of population (P), affluence (A)—measured using GDP per capita—and technology (T). As reviewed by Waggoner and Ausubel (2002), this framework was later adapted into the ImPACT model, which further subdivides technology (T) into two components: consumption per unit of GDP (C) and impact per unit of consumption (T). Additionally, Dietz and Rosa (1994, 1997) introduced a stochastic variant of the model, termed STIRPAT. Subsequent studies (Fan et al., 2006; McGee et al., 2015; Shan et al., 2021; Wang et al., 2021) have incorporated urbanisation in place of population for the variable (P). Some researchers have used the square of GDP per capita to integrate the effects of EKC. EKC is represented by an inverted U-curve, depicting the relationship between GDP and carbon emissions. This study explores the relationship between green technology innovation, green financing, economic growth, and environmental sustainability. The environmental STIRPAT model is employed to assess the effects of these factors on environmental sustainability (Wang et al., 2021).

### 3. 2. DATA AND SOURCES

G7 countries are prominent advocates of green finance and green technology innovations. This study utilises panel data spanning the period from 1990 to 2022, constrained by the lack of data on green financing prior to 1990. The data were sourced from the World Bank, the Energy Institute's *Statistical Review of World Energy*, the Global Footprint Network, and the Organisation for Economic Cooperation and Development (OECD).

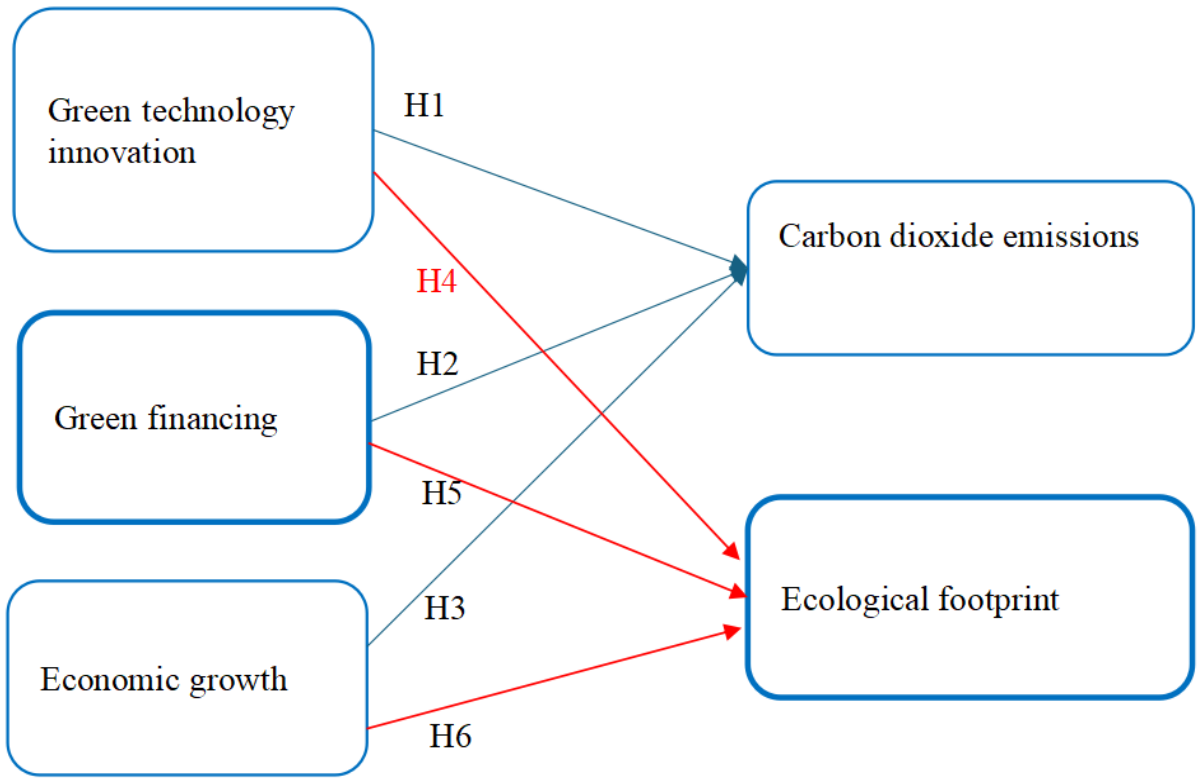
The variables included in the study are CO2 emissions (CO), ecological footprint (EF), green technology innovation (GT), green finance (GF), real GDP per capita (RGDP), and energy consumption (EC). Environmental sustainability is measured by CO2 emissions (CO) in kilotonnes (kt) (X. Wu et al., 2021; Shan et al., 2021) and ecological footprint (EF) (Khan et al., 2024). Green technology innovation (GT) is measured by patents on environmental technologies (Udeagha & Muchapondwa, 2023). Economic growth is measured by real GDP per capita (RGDP) (Mastilo et al., 2024) (constant 2015 US$), while energy consumption (EC) is also

included in the analysis. Green finance (GF) is assessed using the renewable energy public research, development, and demonstration (RD&D) budget. This study found no prior studies that utilised this scale. it uniquely reflects targeted investments in clean energy innovation, directly supports the shift to low-carbon economies, promotes sustainability, reduces dependence on fossil fuels, and achieves environmental and economic sustainability.

### 3. 3. MODEL SPECIFICATION

This study employs two models to explore the nexus of green technology innovation, green financing, economic growth, and environmental sustainability. Model 1 measures environmental sustainability using CO2 emissions, while Model 2 measures it using the ecological footprint. Figure 1 illustrates the expected relationships between these variables.

Figure 1. Study model




Source: Author's design

Based on the research questions and study model, the proposed study hypotheses, as illustrated in Figure 1, are as follows:

*H1: A positive relationship exists between green technology innovation and CO2 emissions.*

*H2: A positive relationship exists between green financing and CO2 emissions.*

*H3: A positive relationship exists between economic growth and CO2 emissions.*

*H4: A positive relationship exists between green technology innovation and ecological footprint.*

*H5: A positive relationship exists between green financing and ecological footprint.*

*H6: A positive relationship exists between economic growth and ecological footprint.*

The selection of model variables was guided by both theoretical and practical considerations. Theoretically, the variables were chosen to align closely with the STIRPAT model,

ensuring their statistical significance and relevance for interpreting the study's phenomena. Practically, the selection was influenced by the availability of relevant data for the G7 countries. Previous studies, such as those by Ibrahim et al. (2023), Jian and Afshan (2023), Shan et al. (2021), Sharif et al. (2022), Temesgen Hordofa et al. (2023), and Khan et al. (2024), determined the model variables by transforming all variables into natural logarithms. This transformation helps create a symmetric, normally distributed dataset, allowing for normal statistical tests, reducing heteroscedasticity, enhancing coefficient estimates, and improving the robustness of regression models. Additionally, using natural logarithms improves the interpretability of economic relationships (Hdom & Fuinhas, 2020). The functional form of the first model is as follows:

$$CO = f(GT, GF, EC, RGDP) \quad (1)$$

$$CO_{it} = \alpha_0 + \alpha_1 GT_{it} + \alpha_2 GF_{it} + \alpha_3 EC_{it} + \alpha_4 RGDP_{it} + \varepsilon_{it1} \quad (2)$$

Where CO represents the CO2 emissions for unit i at time t. GT denotes green technology innovation for unit i at time t, with an expected negative sign. GF signifies green finance for unit i at time t, which is also expected to have a negative sign. EC represents energy consumption for unit i at time t, with an expected positive sign. RGDP indicates the economic growth of unit i at time t, with an expected positive sign. The term  denotes the intercept, and  is the stochastic disturbance term.

The second model is as follows:

$$EF = f(GT, GF, EC, RGDP) \quad (3)$$

$$EF_{it} = \alpha_5 + \alpha_6 GT_{it} + \alpha_7 GF_{it} + \alpha_8 EC_{it} + \alpha_9 RGDP_{it} + \varepsilon_{it2} \quad (4)$$

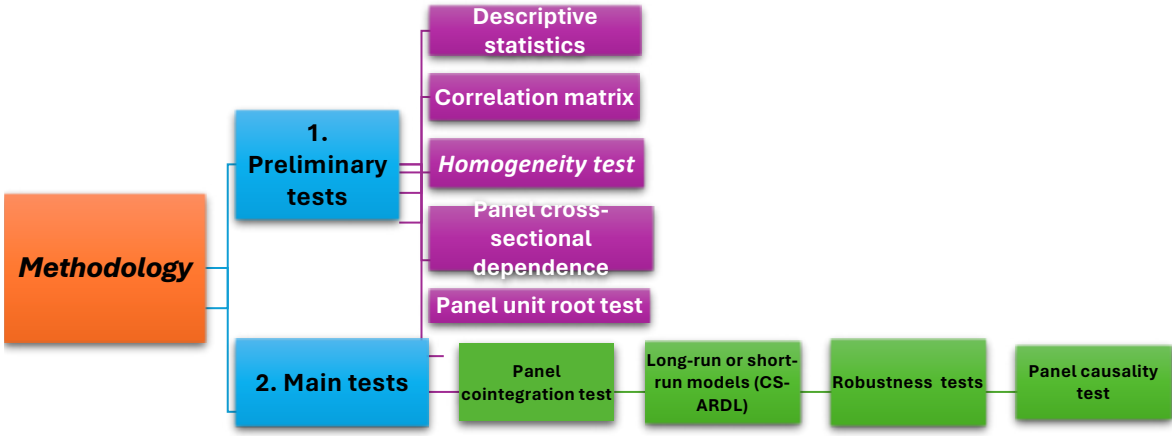
Where EF represents the ecological footprint of unit i at time t. GT denotes the green technology innovation of unit i at time t, with an expected negative sign. GF signifies green finance for unit i at time t, which is also expected to have a negative sign. EC represents energy consumption for unit i at time t, with an expected positive sign. RGDP indicates the economic growth of unit i at time t, with an expected positive sign. The term  denotes the intercept, and  is the stochastic disturbance term.

### 3. 4. METHODOLOGY

A panel cointegration analysis is employed in this study owing to the larger number of time periods (T) compared to cross-sectional units (N). Given that G7 countries share similar environmental, economic, biological, and cultural characteristics, cross-sectional dependence (CSD) is expected (Voumik & Sultana, 2022). To address CSD, second-generation unit root tests and second-generation cointegration methods are utilised.

The methodology is illustrated in Figure 2 and begins with preliminary tests. The importance of these preliminary test approaches lies in their ability to select the optimal model that delivers reliable results. Consequently, the preliminary tests conducted in this study include descriptive statistics, a correlation matrix, skewness and homogeneity tests, assessments of CSD, and unit root tests. Following the preliminary tests, the main analyses include the cointegration test, long- and short-term models, robustness checks, and the panel causality test.

Figure 2. Methodology




Source: Author's design

### 3. 4. 1. CROSS-SECTIONAL DEPENDENCE

The CSD test, proposed by Pesaran (2015), addresses both observed and unobserved common elements, such as economic and financial crises, globalisation, and pandemics (S. Z. Zafar et al., 2023). Omitting this test may lead to biased and misleading results. Thus, in this study, the following methods were applied: CD (Pesaran 2015), CDW (J. Fan et al. 2015), CDW+ (Juodis and Reese 2022), CD* and (Pesaran and Xie 2021).

$$SCD = \sqrt{\frac{2T}{N(N-I)}\left(\sum_{i=1}^{N-1}\sum_{K=i+1}^{N}\overline{(corr}_{i,t})\right)} \tag{5}$$

### 3. 4. 2. PANEL UNIT ROOT TESTS

Unit root tests are conducted to determine the stationarity of the variables. Non-stationary variables can lead to spurious regression results. To assess stationarity in the presence of CSD, this study employs the cross-sectional augmented Dickey-Fuller (CADF) test and the cross-sectional augmented Im, Pesaran, and Schein (CIPS) test, which are classified as second-generation models. These tests help identify spurious results in regression analyses and address issues related to CSD. Additionally, they evaluate the accuracy and robustness of serial variance (Sampene et al., 2022). The CADF is formulated as follows (Sampene et al., 2022):

$$\Delta x_{it} = \propto_{it} + \beta_{it-1} + \partial_1 T + \sum_{j=1}^{N} \gamma_{ij}\, \Delta x_{it-1} + \varepsilon_{it} \tag{6}$$

In this study, the variables are represented by $x_{it}$, the differences between them are indicated by $\Delta$, and $\varepsilon_{it}$ is denotes the stochastic disturbance term. The CIPS formula is expressed as follows (Sampene et al., 2022):

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} \varphi_i(N,T) \tag{7}$$

The parameter $\varphi_i(N,T)$ represents the test statistics from the CADF regression.

### 3. 4. 3. SECOND-GENERATION COINTEGRATION TEST

The cointegration test is used to determine whether the variables are cointegrated, indicating a long-term equilibrium relationship. If the variables are cointegrated, a long-run model can be specified; otherwise, only a short-run model can be developed. This study employs Westerlund's (2007) second-generation cointegration test, which accounts for nonstationary, CSD, and heterogeneous impacts in the data (Voumik & Sultana, 2022). Westerlund's (2007) cointegration test includes Equations (8), (9), (10), and (11) (Voumik & Sultana, 2022).

$$G_\alpha = \frac{1}{N}\sum_{i=1}^{N}\frac{\alpha_i^{/}}{SE(\alpha_i^{/})} \tag{8}$$

$$G_t = \frac{1}{N}\sum_{i=1}^{N}\frac{T\alpha_i^{/}}{\alpha_i^{/}(1)} \tag{9}$$

$$P_t = \frac{\alpha_i^{/}}{(\alpha_i^{/})} \tag{10}$$

$$P_\alpha = T\,\alpha_i^{/} \tag{11}$$

Where $G_\alpha$ and $G_t$ represent group statistics, $P_t$ and $P_\alpha$ indicate second-panel statistics, and $\alpha_i^{/}$ denotes the speed of adjustment from short-term to long-term equilibrium.

### 3. 4. 4. CROSS-SECTIONAL AUTOREGRESSIVE DISTRIBUTED LAGS (CS-ARDL) MODEL

Chudik and Pesaran (2015) developed the CS-ARDL model. This model provides robust results regarding whether the series are cointegrated at the level, first difference, or a combination of both (Chudik et al., 2017; Chudik & Pesaran, 2015). The panel CS-ARDL model addresses endogeneity and CSD, capturing both the long- and short-term impacts of the variables (Ameer et al., 2020). Chudik and Pesaran (2015) emphasised the use of both 'mean group' and 'pooled mean group' estimators in the CS-ARDL estimation methodology. According to CS-ARDL, these two models are expressed as follows:

$$\Delta LCO_{it} = \alpha_{it} + \sum_{j=1}^{p}\beta_{it}\,LCO_{t-j} + \sum_{J=0}^{P}\theta x_{t-j} + \sum_{j=0}^{3}\delta\,\bar{z}_{t-j} + \epsilon_{it} \tag{12}$$

Where represents the logarithm of the independent variables (*LGT, LGF, LEC, LRGDP*). z indicates the average of all cross-sections ($(\Delta\overline{LCO}_t, \bar{x}_t)$).

$$\Delta LFP_{it} = \alpha_{it} + \sum_{j=1}^{p}\beta_{it}\,LFP_{t-j} + \sum_{J=0}^{P}\theta x_{t-j} + \sum_{j=0}^{3}\delta\,\bar{z}_{t-j} + \epsilon_{it} \tag{13}$$

Where represents the logarithm of the independent variables (*LGT, LGF, LEC, LRGDP*). z indicates the average of all cross-sections ($\Delta\overline{LFP}_t, \bar{x}_t$).

### 3. 4. 5. ROBUSTNESS CHECKS

The AMG and CCEMG models are employed to assess the robustness of the results derived from the CS-ARDL model. The CCEMG model, developed by Pesaran (2006), aims to eliminate CSD asymptotically. This model allows for heterogeneous slope coefficients for each group member, which can be obtained by averaging the coefficients of each country. Additionally, the unobserved common effect in the model is captured by the AMG. The AMG employs first-difference OLS for pooled data and is augmented with year dummies (Hussain et al., 2022; C.-C. Lee et al., 2022; Sharif et al., 2023; Voumik et al., 2023).

### 3. 4. 6. PANEL CAUSALITY TEST

A panel causality test is conducted to determine potential causal linkages among the variables within the panel data. While the CS-ARDL estimation approach provides long-run coefficients, it does not indicate the causal direction among covariates (Zhang et al., 2023). To examine the relationships among LGT, LGF, LEC, and LRGDP, this study utilises the panel causality analysis proposed by Dumitrescu and Hurlin (2012). This method accommodates heterogeneity and conditional dependence, yielding consistent results even with limited data (Zhang et al., 2023).

## 4. THE EMPIRICAL RESULTS AND DISCUSSION

The experimental results are presented in two subsections: preliminary results and main results. The preliminary results include descriptive statistics, a correlation matrix, and unit root tests. The main results encompass the cointegration tests, anchored CS-ARDL, robustness checks (CCEMG and AMG), and causality tests.

### 4. 1. PRELIMINARY TESTS

### 4. 1. 1. DESCRIPTIVE STATISTICS AND CORRELATION MATRIX

Table 1 presents the descriptive statistics, including the mean, standard deviation, and minimum and maximum values. Notably, several variables exhibit large standard deviations, occasionally surpassing the mean, signifying substantial variability in the data. This pronounced variation may be attributed to economic crises, which introduced considerable volatility, underscoring a turbulent economic environment during the study period.

Table 1. Descriptive statistics and correlation matrix

| Variable | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|
| CO | 1271198 | 1640701 | 267154.7 | 5775807 |
| EF | 5.415094 | 1.960818 | 2.429361 | 10.92681 |
| RGDP | 40849.67 | 6265.394 | 29460.48 | 61855.53 |
| GT | 9.883256 | 2.790776 | 5.134481 | 16.23065 |
| EC | 23.7077 | 28.24268 | 5.947064 | 97.42963 |
| GF | 14.4439 | 9.141725 | .57 | 51.47 |

Source: Author's analysis

### 4. 1. 2. CORRELATION MATRIX

Table **2** presents the results of the correlation analysis. The results indicate that CO is positively associated with RGDP and EC, but negatively correlated with GT and GF. Similarly, EF shows a positive association with RGDP and EC, while exhibiting a negative correlation with GF and GT.

Table 2. Correlation matrix

| Variables | EF | CO | RGDP | GT | EC | GF |
|---|---|---|---|---|---|---|
| EF | 1.000 | | | | | |
| CO | 0.824 | 1.000 | | | | |
| RGDP | 0.363 | 0.616 | 1.000 | | | |
| GT | -0.361 | -0.149 | 0.402 | 1.000 | | |
| EC | 0.796 | 0.995 | 0.649 | -0.138 | 1.000 | |
| GF | -0.040 | -0.202 | 0.198 | 0.364 | -0.209 | 1.000 |

Source: Author's analysis

### 4. 1. 3. HOMOGENEITY TEST

Table 3 shows that the p-value (0.000) from the test is below 5%. Therefore, the null hypothesis is rejected, indicating that the slope coefficients are heterogeneous.

Table 3. Homogeneity test

| Delta | p-value |
|---|---|
| 7.442 | 0.000 |
| adj. 8.228 | 0.000 |

Source: Author's analysis

### 4. 1. 4. CROSS-SECTIONAL DEPENDENCE

This study utilises the Pesaran CD, CDW, CDW+, and CD* tests to confirm CSD. The results are presented in Table 4.

Table 4. Cross-sectional dependence test

| Variable | CD | CDW | CDW+ | CD* |
|---|---|---|---|---|
| CO | 10.860<br>(0.000) | -0.870<br>(0.385) | 72.270<br>(0.000) | -2.610<br>(0.009) |
| RGDP | 22.460<br>(0.000) | -3.940<br>(0.000) | 99.000<br>(0.000) | -3.000<br>(0.003) |
| EC | 10.400<br>(0.000) | 2.850<br>(0.004) | 69.960<br>(0.000) | -7.850<br>(0.000) |
| EF | 15.290<br>(0.000) | -1.000<br>(0.320) | 77.580<br>(0.000) | 1.810<br>(0.071) |
| DF | 9.350<br>(0.000) | -2.810<br>(0.005) | 45.430<br>(0.000) | 2.940<br>(0.003) |
| GT | 24.200<br>(0.000) | -3.510<br>(0.000) | 107.400<br>(0.000) | 1.960<br>(0.050) |

Source: Author's analysis

The null hypothesis of CSD (correlation) is rejected for all variables at the 1% significance level, indicating a strong dependence between the cross-sections average in the data. Unit root tests of the second generation should be employed to investigate the integration characteristics of the variables when CSD is present.

### 4. 1. 5. STATIONARY TESTS

This study employs panel unit root tests that account for CSD, specifically Pesaran's CADF and Pesaran-CIPS unit root tests, which are suitable when T is greater than N. These tests are referred to as second-generation models. When CSD is present, the unit root tests from second-generation models yield robust results, as shown in Table 5.

Table 5. Panel unit root test

| Variables | CIPS statistic constant & trend | | Pesaran's CADF test constant & trend | |
|---|---|---|---|---|
| | I(0) | I(1) | I(0) | I(1) |
| Co | -1.571 | -5.462 *** | -0.048 | -3.316*** |
| GT | -3.448 *** | -5.370 *** | -1.384 | -4.945*** |
| GF | -2.997 *** | -5.750 *** | -0.143 | -1.700** |
| EC | 0.336 | -6.187 *** | 1.772 | -3.080*** |
| RGDP | -1.666 | -4.818 *** | 0.380 | -1.679** |
| EF | -2.556** | -5.606 *** | -1.211 | -4.552*** |

***, **, and * explain the significance level at 1%, 5%, and 10%, respectively.

Source: Author's analysis

Table 5 shows that the null hypothesis is rejected for all variables at the 5% significance level across all tests, indicating that all variables are stationary at the first difference.

## 4. 2. MAIN TESTS

### 4. 2. 1. PANEL COINTEGRATION TEST

When the variables are stationary at the same order of integration, verifying their long-term integration is essential. This study employs the Westerlund cointegration test and second-generation models to assess whether the variables are significantly related in a long-run association.

Table 6 shows that the null hypothesis is rejected at the 5% significance level based on the robust p-value for (Gt, Ga, and Pt). This indicates that the variables are cointegrated in the long term.

Table 6. Westerlund cointegration test

| Statistic | value | Z-value | P-value | Robust P-value |
|---|---|---|---|---|
| Gt | -2.139 | -1.912 | 0.028 | 0.040 |
| Ga | -9.493 | -1.775 | 0.038 | 0.040 |
| Pt | -8.129 | -4.252 | 0.000 | 0.010 |
| Pa | -8.093 | -3.020 | 0.001 | 0.110 |

Source: Author's analysis

### 4. 2. 2. OPTIMAL MODELS

The applied tests demonstrate the existence of CSD, confirm that all variables are stationary at the first difference, and establish that the variables are cointegrated. Consequently, the optimal model is a second-generation panel ARDL model.

Table 7 presents the findings on the impacts of green technology innovation, green financing, and environmental sustainability based on the CS-ARDL model. According to the CO2 emissions model, the elasticity coefficient for green technology innovation (GT) is statistically significant at the 5% level. On average, a 1% increase in GT results in a 0.11% decrease in CO2 emissions. This indicates that green technology innovation negatively affects CO2 emissions in G7 countries, suggesting an expected improvement in environmental quality. However, consistent with previous short-term findings (Temesgen Hordofa et al., 2023; Jian & Afshan, 2023; Sharif et al., 2022; Zhang et al., 2022; Huang et al., 2021; Feng et al., 2009; Shan et al., 2021), green technologies may not significantly reduce CO2 emissions for several reasons. The development of renewable energy infrastructure and other green technologies requires substantial energy and resource consumption, which can initially lead to increased emissions. Furthermore, delays in integrating these technologies into economic systems prolong reliance on conventional polluting technologies, reducing the anticipated immediate decrease in emissions. Regula-

tory challenges and behavioural inertia also hinder the swift adoption of green technologies, further limiting their short-term impact. Consequently, significant reductions in CO2 emissions from green technologies typically emerge only in the long term.

Table 7. Results of CS-ARDL analysis

| Variables | CO model | | Variables | EF model | |
|---|---|---|---|---|---|
| Short-term | Coef. | P>z | Short-term | Coef. | P>z |
| ECT (−1) | -0.1657** | 0.0470 | ECT (−1) | 0.2613*** | 0.0010 |
| D.LGT | -0.0201 | 0.1660 | D.LGT | -0.0002 | 0.9850 |
| D.LGF | -0.0112*** | 0.0060 | D.LGF | -0.1048 | 0.1790 |
| D.LRGDP | 0.2708** | 0.0111 | D.LRGDP | 0.4945*** | <0.0000 |
| D.LEC | 0.9005*** | <0.0000 | D.LEC | 0.6604** | <0.0000 |
| Long-term | | | | | |
| lr_LRGDP | 0.2845** | 0.0320 | lr_LRGDP | -0.3519*** | <0.0000 |
| lr_LGF | - 0.0530** | 0.0180 | lr_LGF | - 0.0546 | <0.0000 |
| lr_LGT | - 0.1104** | 0.0010 | lr_LGT | -0.1130* | 0.0100 |
| lr_LEC | 0.6369*** | <0.0000 | lr_LEC | 1.2649 *** | <0.0000 |

***, **, and * explain the significance level at 1%, 5%, and 10%, respectively.

Source: Author's analysis

The elasticity coefficient for green financing (GF) is also statistically significant at the 5% level. On average, a 1% increase in GF leads to a 0.02% decrease in CO2 emissions in the short-term and a 0.05% decrease in the long term. These results suggest that green financing negatively impacts CO2 emissions in G7 countries, indicating an overall environmental improvement. This aligns with earlier findings by Ibrahim et al. (2023), Feng (2022), Jian and Afshan (2023), Sharif et al. (2022), and Saeed Meo & Karim (2022). The elasticity coefficient for energy consumption (EC) is statistically significant at the 5% level as well. On average, a 1% increase in EC results in a 0.90% increase in CO2 emissions in the short-term and a 0.63% increase in the long term. This indicates that energy consumption positively affects CO2 emissions in G7 countries, highlighting a need for policy changes to reduce reliance on non-renewable energy over time. The elasticity coefficient for economic growth (RGDP) is statistically significant at the 5% level. On average, a 1% increase in RGDP leads to a 0.27% increase in CO2 emissions in the short-term and a 0.28% increase in the long term. These findings demonstrate that economic growth positively impacts CO2 emissions in G7 countries, consistent with EKC theory and supporting previous research by Sharif et al. (2022) and Akbostancı et al. (2009). Finally, the error correction term (ECT (−1)) coefficient is negative and statistically significant at the 5% level, indicating that the system will adjust to long-term equilibrium after any shock, with a correction rate of 17% in the following year.

According to the ecological footprint model findings, the elasticity coefficient for green technology innovation (GT) is statistically significant at the 5% level. On average, a 1% increase in GT leads to a 0.11% decrease in the ecological footprint in the long term. This indicates that green technology innovation negatively impacts the ecological footprint of G7 countries over time. Investments in green technology innovation promote infrastructure development, which significantly reduces resource consumption and emissions, contributing to greater environmental sustainability (Moraliyska, 2023). This finding aligns with previous research by Saqib et al. (2024), Ibrahim et al. (2023), Sharif et al., (2022), Huang et al. (2021), Temesgen Hordofa et al. (2023), and Feng et al. (2009). In the short term, GT does not significantly affect the ecological

footprint due to slow adoption rates, infrastructure constraints, and high initial costs. During this period, existing non-renewable systems continue to dominate, which reduces the short-term ecological impacts.

The elasticity coefficient for green finance (GF) is also statistically significant at the 5% level. On average, a 1% increase in GF results in a 0.05% decrease in the ecological footprint in the long term. This suggests that green financing negatively influences the ecological footprint of G7 countries, indicating an expected environmental improvement, as supported by findings from Saqib et al. (2024), Gong et al. (2024), and Sampene et al. (2022). Long-term green financing is crucial for reducing the ecological footprint by channelling resources into renewable energy, energy efficiency, and sustainable practices. As green initiatives become more operational and widely adopted, their cumulative effects will lead to significant reductions in resource consumption and environmental damage, making green finance an effective tool for long-term ecological sustainability. In the short term, however, GF does not significantly affect the ecological footprint due to the time required for investments to materialise and for environmentally friendly projects to yield measurable results. The initial implementation phases often involve extensive planning, regulatory changes, and the development of green infrastructure, which delays their direct impacts.

The elasticity coefficient for energy consumption (EC) is statistically significant at the 5% level. On average, a 1% increase in EC leads to a 0.66% increase in the ecological footprint in the short-term and a 1.26% increase in the long term. These results indicate that energy consumption positively impacts the ecological footprint of G7 countries, which is further supported by research from Saqib et al. (2024).

The elasticity coefficient for economic growth (RGDP) is also statistically significant at the 5% level. On average, a 1% increase in RGDP results in a 0.49% increase in the ecological footprint in the short term. This finding suggests that RGDP positively impacts the ecological footprint of G7 countries in the short term. However, in the long term, a 1% increase in RGDP leads to a 0.39% decrease in the ecological footprint. This outcome contradicts expectations and can be explained by the fact that, over time, countries may adopt more sustainable policies, technological innovations, and effective environmental legislation to reduce their ecological footprint while continuing to promote economic growth. Finally, the error correction term (ECT (-1)) coefficient is negative and statistically significant at the 5% level, indicating that the system will adjust to long-term equilibrium after any shock, with a correction rate of 26% in the following year.

### 4. 2. 3. ROBUSTNESS CHECKS

The results of the CCEMG and AMG estimates presented in Table 8 indicate that the findings from the CS-ARDL estimations are consistent in the long term, exhibiting nearly identical coefficients and signs.

Table 8. Results of CCEMG and AMG

| | CCEMG | | | | AMG | | | |
|---|---|---|---|---|---|---|---|---|
| Variables | CO Model | | EF Model | | CO Model | | EF Model | |
| | Coefficient | Pro | Coefficient | Pro | Coefficient | Pro | Coefficient | Pro |
| lRGDP | 0.2845 | 0.003 | -0.3519 | <0.000 | 0.278 | <0.000 | -0.390 | 0.005 |
| lGT | -0.1104 | 0.001 | -0.1130 | <0.000 | -0.182 | 0.019 | -0.199 | 0.003 |
| lGF | -0.0503 | 0.018 | -0.0546 | <0.000 | -0.099 | <0.000 | -0.080 | 0.001 |
| lEC | 0.6369 | <0.000 | 1.264 | <0.000 | 1.079 | <0.000 | 0.987 | <0.000 |

Source: Author's analysis

### 4. 2. 4. DUMITRESCU–HURLIN CAUSALITY TEST RESULTS

Table 9 confirms that the D&H panel causality test results align with those from the CS-ARDL, CCEMG, and AMG estimators. The statistical significance of the Z-statistics indicates that the null hypothesis can be rejected, suggesting that green technology innovation (LGT) and LEC do not homogeneously cause CO2 emissions (LCO). Therefore, LGT, LEC, and LCO have homogeneous bi-causal relationships. Additionally, LGT and green financing (LGF) do not homogeneously cause LEF, resulting in homogeneous bi-causal relationships among, LGT, LEC, and LEF. In contrast, the null hypothesis that LRGDP and LGF are homogeneous causes of CO2 emissions (CO) cannot be rejected. This implies that LRGDP, LGF, and LCO exhibit a homogeneous uni-causal relationship. Furthermore, a uni-causal relationship can be inferred between LRGDP, LGF, and LEF. Notably, no causal relationship exists between ecological footprint and growth. This study supports the idea that economic activity primarily influences environmental effects. It indicates a partial decoupling of economic growth from environmental harm, suggesting that developed economies such as those in the G7 can manage environmental implications through economic growth policies without facing short-term negative effects on growth due to environmental deterioration.

Table 9. Dumitrescu–Hurlin causality test results

| Carbon dioxide emissions model | | | | |
|---|---|---|---|---|
| Causality | W-stat | Z-stat | Prob. | Result |
| LRGDP---- LCO<br>LCO-------LRGDP | 5.4425<br>1.3306 | 4.5540<br>-0.8855 | 0.0000<br>0.3759 | Homogeneous Uni-causal relationship |
| LGT--------- LCO<br>LCO------- LGT | 6.4554<br>5.8747 | 5.8939<br>5.1258 | <0.000<br><0.000 | Homogeneous Bi-causal relationship |
| LGF-------- LCO<br>LCO------- LGF | 7.3474<br>2.6281 | 7.0739<br>0.8310 | <0.000<br>0.4060 | Homogeneous Uni-causal relationship |
| LEC-------- LCO<br>LCO------- LEC | 5.4134<br>5.2066 | 4.5156<br>4.2419 | <0.000<br><0.000 | Homogeneous Bi-causal relationship |
| Ecological footprint model | | | | |
| Causality | W-stat | Z-stat | Prob. | Result |
| LRGDP----- LEF<br>LEF ------ LRGDP | 10.1275<br>0.9069 | 10.7517<br>-1.4460 | <0.000<br>0.1482 | Homogeneous Uni-causal relationship |
| LGT--------- LEF<br>LEF -------- LGT | 6.3212<br>4.1396 | 5.7164<br>2.8305 | <0.000<br>0.0046 | Homogeneous Bi-causal relationship |
| LGF-------- LEF<br>LEF ------- LGF | 6.7316<br>2.8561 | 6.2593<br>1.1325 | <0.000<br>0.2574 | Homogeneous Uni-causal relationship |
| LEC-------- LEF<br>LEF --------LEC | 5.3237<br>5.3985 | 2.5098<br>4.4958 | 0.0121<br><0.000 | Homogeneous Bi-causal relationship |

Source: Author's analysis

## 5. CONCLUSIONS

This study examines the impact of green technology innovation, green financing, and economic growth on environmental sustainability in G7 economies from 1990 to 2022. To the best of my knowledge, only one prior study has explored the effects of green technology innovation and finance on CO2 emissions in G7 countries. Building on this work, the present study broadens the scope by assessing environmental sustainability using two indicators: CO2 emissions and the ecological footprint. The preliminary analysis involved descriptive statistics, a correlation matrix, cross-sectional dependence (CSD) tests, skewness and kurtosis tests for normality, and

unit root tests. The results reveal strong cross-sectional dependence, with all variables found to be stationary at the first difference. Accordingly, the study employed the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) approach to analyse both the long-term and short-term dynamics of environmental sustainability.

The CO2 emissions model revealed that green financing, energy consumption, and economic growth have varying effects on CO2 emissions in G7 countries. Green financing has a negative impact, while energy consumption has a positive effect. Real GDP also positively influences emissions. The error correction term coefficient suggests that the system will adjust to long-term equilibrium after any shocks, with a correction rate of 17% in the following year. These findings support the EKC theory. Green technology innovation negatively affects CO2 emissions in G7 countries. Specifically, a 1% increase in green technology innovation results in a 0.11% decrease in emissions in the long term. However, short-term benefits may be limited owing to initial energy consumption, delayed integration into economic systems, and regulatory challenges. Although green technologies may lead to temporary increases in emissions from conventional polluting technologies, their long-term benefits are significant. Investments in green technology innovation foster infrastructure development, reduce resource consumption and emissions and enhance environmental sustainability. In the short term, green technology innovation has minimal impact on CO2 emissions due to infrastructure constraints and high initial costs. Green financing plays a crucial role in reducing emissions by directing resources toward renewable energy, energy efficiency, and sustainable practices.

The ecological footprint model revealed that green technology innovation negatively impacts the ecological footprint of G7 countries in the long term. It promotes infrastructure development while reducing resource consumption and emissions. However, in the short term, green technology innovation does not influence the ecological footprint owing to infrastructure constraints and high initial costs. Green financing also negatively affects the ecological footprint, but it is essential for long-term ecological sustainability. In contrast, energy consumption positively impacts the ecological footprint. While real GDP positively affects the ecological footprint of G7 countries in the short term, it decreases the ecological footprint in the long term. G7 countries often adopt sustainable policies, technological innovations, and effective environmental legislation to reduce their ecological footprint and enhance economic growth over time. The error correction term coefficient is negative and statistically significant at the 5% level, indicating that the system will adjust to long-term equilibrium after any shock.

Robustness checks using the CCEMG and AMG estimates demonstrate long-term results consistent with the CS-ARDL estimations, with nearly identical coefficients and signs. D&H causality findings suggest that policies promoting green technology innovation and energy consumption significantly affect CO2 emissions and the ecological footprint, and vice versa. Conversely, policies related to green finance and economic growth significantly influence CO2 emissions and the ecological footprint, while changes in CO2 emissions and the ecological footprint do not impact green finance and economic growth.

## 5. 1. IMPLICATIONS

The findings indicate that while economic expansion increases the environmental footprint and CO2 emissions in the short term, it reduces the environmental footprint in the long term, aligning with sustainable development models, such as the EKC. Green financing and technology innovation enhance long-term environmental sustainability. However, green technology innovation does not impact the environmental footprint in the short-term but offers long-term benefits for sustainability. These findings emphasise the significance of balanced policies that prioritise green finance in the short-term to mitigate environmental impacts while promoting long-term

investments in technological innovation. Additionally, increasing international cooperation and aligning investments with green goals are crucial for achieving sustainable growth while minimising environmental damage.

## 5. 2. RECOMMENDATIONS

This study recommends several measures to enhance sustainability, including strengthening green financing mechanisms, promoting green technological innovation, balancing economic growth with sustainability goals, monitoring environmental indicators, and raising awareness about the benefits of green financing and technological innovation. These initiatives can encourage firms to adopt cleaner technologies, reduce their carbon footprint, and realise long-term benefits.

To strengthen the inverse relationship between economic growth and the environmental footprint, this study recommends that governments enforce strict emission regulations, prioritise renewable energy investments, develop public awareness campaigns, and foster collaboration between businesses, governments, and academia. This collaboration can encourage the adoption of cleaner technologies, investment in renewable energy, and promotion of sustainable solutions for economic growth. Additionally, promoting the concept of a circular economy—where resources are reused and recycled—can help reduce waste, carbon emissions, and the environmental footprint. Ultimately, developing more sustainable strategies that support economic growth without compromising environmental sustainability is essential.

## 5. 3. LIMITATIONS

This study has some limitations. First, it assumes that green financing and technology innovation provide immediate sustainability benefits. However, transitioning to greener economies requires long-term investments, particularly in infrastructure projects, which may require years to yield environmental effects. This temporal lag poses challenges in assessing the immediate effectiveness of green funding programs. Additionally, while this study focuses on CO2 emissions and the ecological footprint, other environmental indicators—such as water usage, declining biodiversity, and waste management—were overlooked, limiting the scope of the analysis on environmental sustainability. Future studies could broaden their scope to include the top 20 economies, as well as BRICS and OECD countries. Moreover, future studies could examine the impact of green financing through environment-related tax revenue and government R&D budgets dedicated to environmental initiatives.

### Conflict of interest

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