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RESEARCH ARTICLE

Effects of economic complexity, economic growth, and renewable energy technology budgets on ecological footprint: the role of democratic accountability

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Abstract

The economic structure of countries can influence economic growth, energy demand, and environmental footprints. However, the literature on economic complexity and ecological footprint (EFP) nexus is scarce. Besides, democracy is an important factor that may affect environmental policies and environmental sustainability. Hence, this paper investigates the effect of democracy, economic complexity, and renewable energy technology budgets on the EFP in G7 countries controlling income and financial development from 1985 to 2017. The findings from Westerlund (*J Appl Econ* 23:193–233, 2008) and other cointegration methods depict cointegration among variables. The long-run estimates from the continuously updated fully modified method unfold that economic complexity contributes to reducing the EFP. However, greater democratic accountability boosts the EFP figures rather than reducing them. On the flipside, renewable energy technology budgets and financial development are evidenced to mitigate EFP. Moreover, the study unveils a U-shaped linkage between economic growth and EFP, which indicates that an increase in income level will boost EFP. Further, the study found causality from economic complexity, democracy, and renewable energy budgets to EFP. Based on these findings, it is pertinent for the G7 countries to increase the manufacturing of sophisticated and complex products. In addition, enhancing renewable energy technology budgets is essential to ensure environmental well-being.

Keywords Economic complexity · Democratic accountability · Ecological footprint · Renewable energy technology budgets · Income

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Introduction

Over the last decade, studies linking economic development and ecological footprint (EFP) are steadily increasing because countries' environmental footprints have gone beyond the biosphere's productive capacity (biocapacity). Consequently, most countries are facing an ecological deficit (Sinha et al. 2019; Ahmed et al. 2020a; Xue et al. 2021). EFP is a comprehensive metric that tracks humanity's resource consumption and waste generation in terms of bioproductive areas (Nathaniel 2021a; Tillaguango et al. 2021). It is necessary to control the growth in the ecological footprints since an uninterrupted state of ongoing ecological deficit can cause food shortage, biodiversity loss, and climate change, among others (Ahmed et al. 2020a, 2021a).

A plethora of research on EFP has remarked economic development a prime cause of rising EFP (Zeraibi et al. 2021; Murshed et al. 2021). According to Shahbaz et al. (2019), economic development is necessary to attain human beings' welfare; however, there is a trade-off between development and environmental deterioration since development requires resource consumption. According to Bekun et al. (2021) and Ahmed et al. (2021c), countries prioritize development over the environment at the initial development stage. Hence, efforts to enhance production and consumption pollute the environment through the scale effect. After this stage, structural changes in the economy help mitigate the rate of environmental pollution since the process of development leads to the transition from agricultural to industrial and finally to the service sector, which generates less environmental damage (Ulucak and Bilgili 2018). Further, with more development, society prioritizes the environment over income and focuses on building green technology, investing in clean energy, and developing stringent environmental laws. At this stage of high development, the dominating role of the technique effect tends to decline ecological degradation leading to the environmental Kuznets curve (EKC) hypothesis (Orhan et al. 2021; Ahmed et al. 2021c). In empirical investigations, many studies support these arguments and suggest the EKC (inverted U-shaped relation) between economic growth (Y) and EFP (Ahmed et al. 2021c; Ahmed & Wang 2019; Danish et al. 2019; Shan et al. 2021; Hassan et al. 2019; Katircioglu et al. 2018; Ozturk et al. 2016) while some scholars disclose a U-shaped nexus between these variables (Odugbesan and Adebayo 2020; Soylu et al. 2021; Ahmed et al. 2020a; Charfeddine 2017; Doğan et al. 2020). Hence, the relation between Y and EFP involves controversies, and it is expected that this relationship is sensitive to the selection of variables, methodologies, and sample countries.

Nevertheless, from this discussion, it is also evident that structural changes in the economy are among the important factors that may contribute to reducing environmental damage. Additionally, environmental outcomes are tied with cleaner energy research and development budgets (RD) and environmental laws, which depend on political institutions. Hence, this work intends to study the effects of economic complexity (EC), democracy (DA), economic growth, and cleaner energy budgets on EFP in the presence of financial development (FD).

EC can be defined as the skill and knowledge-based refined production structure of a nation that generates significant output. Hidalgo and Hausmann (2009) extensively criticized the traditional production approach that relies on labor and capital but ignores various capabilities, i.e., non-tradable services and goods, including skilled labor, regulations, infrastructure, and property rights. EC intends to capture economies' production features by accounting for capabilities, and this index is based on the export basket. The more value of the EC index signifies more sophisticated production capabilities of a nation's production structure. EC can impact EFP according to the development level of countries; for instance, at an initial stage of development, underdeveloped nations strive to specialize in the agriculture sector, and at this stage, economic complexity, energy demand, and environmental damage are usually low (Gyamfi et al. 2021; Ramzan et al. 2021; Apergis et al. 2018). The sophisticated knowledge-based complexed products are generally started to be developed when countries enter the developing group (Can & Gozgor 2017).

Nevertheless, the efforts to develop complex products initially lead to the development of energy-intensive products like metal, textile, and cement. That pollutes the environment (Hu et al. 2020). At this stage, EC can upsurge EFP. However, with more development, the tendency to dump energy-intensive products from the export basket increases due to change in society's preferences. Hence, at a high level of development, economies develop complex knowledge-based products requiring fewer resources (Doğan et al. 2019), leading to reduced environmental footprints. Moreover, the better the economic structure through the innovative process, the more efficient and diversified the utilization of energy. Energy efficiency improvement along with renewable energy transition can collectively ensure that resources, especially fossil fuels, are extracted and consumed, whereby EFP can be expected to decline. The study of Can and Gozgor (2017) and Doğan et al. (2019) established a negative relation between EC and CO_2 emissions which infers that EC decreases environmental degradation. On the flipside, Hausmann et al. (2011) and Neagu and Teodoru (2019) established that EC exerts a positive impact on CO_2 emissions, which implies an increase in environmental degradation accompanies an increase in EC. The recent study of Martins et al. (2021) also suggested that EC and CO_2 are negatively linked in the countries with the highest levels of economic complexity. In the context of EC and EFP, Ahmad et al. (2021a) claimed that EC enhances EFP in emerging nations; however, a higher level of EC helps reduce EFP. On the contrary, Nathaniel (2021b) unfolded that enhancing the level of EC boosts EFP in ASEAN countries.

Evidently, governing environmental policies is an important role of countries' political institutions; therefore, this work considered democracy which is a vital institutional variable. The study of Akalin and Erdogan (2020) illustrated the crucial role of democracy in increasing the EFP for Organisation for Economic Co-operation and Development (OECD) countries, which can be questioned because theoretical background suggests that democracy can alleviate or upsurge ecological degradation. In the view of Payne (1995), democratic nations possess more access to information and freedom of speech. The former can stimulate environmental awareness, while the latter can encourage the general public to demand a cleaner environment and even protest to pressurize governments. Similar arguments are made in the study of Farzin and Bond (2006) that democracy can alleviate environmental problems because freedom of speech and access to information play a vital role in increasing democratically elected governments' responsiveness. Democratic regimes build effective environmental institutions that invest in nurturing awareness among the general public regarding the environment. Also, better accountability and more public participation in decision-making can help improve the environment, while most of these factors are generally missing in autocratic regimes (Güngör et al. 2021). Following these arguments, the empirical studies of Lv (2017) and Adams and Acheampong (2019) proved that democracy decreases emissions in emerging economies and African countries, respectively. Also, studies of Heilbronner (1974), Midlarsky (1998), and Roberts and Parks (2007) have provided evidence of the negative relationship between CO_2 emissions and democracy. Besides, democracy can play an important role in allocating more RD, which can benefit the environment.

However, some scholars contradict these views. As discussed earlier, Akalin and Erdogan (2020) unfold that democracy contributes to increasing EFP in the OECD countries. Moreover, evidence of positive linkage between democracy and CO_2 emissions is empirically established by Winslow (2005) and Mak Arvin and Lew (2011). The study of Wang et al. (2018) also discloses that democracy is positively linked with the PM 2.5 level in the context of G20 nations. They believe that democracy cannot improve environmental quality except for some immature economies where it may help in managing immature economic systems, which may improve environmental quality. These scholars believe that generally, at a high development level, democratic regimes opt to protect economic interests than the environmental ones. Empirical investigations by Joshi and Beck (2018) and Pellegrini and Gerlagh (2006) also could not find the environmental benefits of democracy in the context of reducing emissions levels. Moreover, Usman et al. (2019) and Roberts and Parks (2008) suggest that the effect of democracy on the environment can be explained in the context of modernization theory because democracy is linked with economic development. In fact, democracy helps increase income levels, and with an upsurge in income, resource consumption rises, which, in turn, intensifies environmental degradation.

Besides, Ardito et al. (2019) argue that public sector RD is essential to secure economic interests and develop green energy technologies. The possible turning point in the EKC hypothesis depends a lot on cleaner energy consumption that is tied with the research and development in cleaner energy. Hence, RD can enable nations to shift towards green energy and reduce fossil fuel usage gradually. According to Koçak and Ulucak (2019), energy technology budgets help achieve environmental sustainability, reduce energy insecurity, and accomplish economic goals. For instance, Garrone and Grilli (2010), Jin et al. (2017), Koçak and Ulucak (2019), TÖztürk et al. (2020), and Altıntaş and Kassouri (2020) found a negative connection between RD and CO_2 emissions, which implies that an increase in RD decreases environmental degradation. On the contrary, the study of Cheng et al. (2017), Garrone and Grilli (2010), and Amri (2018) established an insignificant linkage between RD and CO_2 emissions. A possible reason for the above outcomes can be the low level of RD in the selected countries.

This paper probes the impact of economic complexity, democracy, economic growth, and renewable energy technology budgets (RD) on EFP in the context of G7 countries. G7 nations are selected for the study because they are greatly developed and possess the most advanced economic structure in the world. Also, most of the member countries ranging from the United States of America (USA) are seen as stakeholders in the democratic execution of the countries' affairs with strong institutional operations. All these countries have strong democracies; therefore, it would be interesting to understand how sophisticated economic structure and strong democratic accountability influence EFP. These nations are characterized by high EFP, and five of these nations are among the list of top ten countries in terms of EFP (Ewing et al. 2010). Additionally, approximately 46% contribution to the world's GDP and enormous consumption of fossil energy sources make these countries unique (Ahmed et al. 2020a, b).

Our study is distinguished from other studies and contributes to the literature in the following way. Firstly, we analyze the effects of democracy and economic complexity on EFP in G7 countries. According to the best of our knowledge, this is the first empirical attempt to investigate the impact of these variables on the EFP in the G7 context.

Secondly, this study includes RD in the model because these budgetary allocations can play a stimulating role in improving the environment (Ahmed et al. 2021d). Thirdly, we used reliable econometric methodologies, such as continuously updated fully modified (CUP-FM) and continuously updated bias-corrected (CUP-BC) methods that account for fractional integration, autocorrelation, cross-sectional dependence (CD), heteroscedasticity, and endogeneity problems in the panel datasets. Our study will be a blueprint for other countries globally, especially the developing nations in managing their environmental performance. The remainder of this paper is organized as follows. The section "Empirical methodology and data" provides data and methodology, the section "Empirical findings and discussions" presents empirical results and discussion, and the section "Conclusion and policy directions" provides concluding remarks.

Empirical methodology and data

Theoretical foundation and description of variables

In recent decades, a growing number of environmental studies assess the driving forces of environmental deterioration by using different methodologies and different measures of environmental damage (Wu et al. 2021, 2020; Ahmed and Wang 2019; Wu et al. 2022; Ahmed et al. 2020a; Tirgil et al. 2021; Wang et al. 2021; Al-Mulali & Ozturk 2016; Li et al. 2021; Rjoub et al. 2021; Lan et al. 2021; Ozturk et al. 2016; Quan et al. 2021; Yu et al. 2015; Bekun et al. 2021). In this study, we opted for a comprehensive measure of environmental degradation, the EFP following recent studies of Ahmed et al. (2021b), Kirikaleli et al. (2020), and Zhang et al. (2021). As per the theoretical underpinnings of the EKC hypothesis, economic growth affects environmental degradation in three phases, namely scale, composition, and technique effects (Ma et al. 2021; Ahmad et al. 2021b; Adebayo & Rjoub 2021; Akinsola et al. 2021; Adebayo & Acheampong 2021; Shahbaz et al. 2022; Kihombo et al. 2021b). In the first phase, ecological degradation is enhanced but after reaching a threshold level, the environmental quality begins to improve due to structural changes, technological advancement, and an increase in environmental consciousness. The first phase (scale effects) is related to developing nations because non-renewable energy sources promote their economic and production activities (Rjoub et al. 2021; Shahbaz and Sinha 2019). The technique and composition effects are linked with the turning point (Shahbaz et al. 2020). These stages can prevail in developed countries, where most of their economic activities are service and technology-driven.

Conversely, studies also believe that the high-income level can even intensify ecological degradation (Charfeddine 2017; Doğan et al. 2020; Lin et al. 2021). We have already discussed in the "Introduction" section that economic complexity (a sophisticated production structure) and democracy can reduce or upsurge EFP, and RD may also influence EFP levels. Also, the turning point of the EKC depends a lot on structural changes (Can & Gozgor 2017) and cleaner energy investments that drive innovation. Thus, the addition of EC and RD in the EKC framework is quite reasonable. Moreover, the role of political institutions in formulating and governing ecological policies is undeniable, and environmental policies at a high-income level play an important role in the reduction of the harmful environmental effects of economic growth (Kirikkaleli et al. 2021; Ahmed and Wang 2019). We also add FD in the model because FD can help in decreasing EF if the financial sector focuses on investing in green energy projects. Conversely, the lending for infrastructure development and other projects may enhance EFP (Kihombo et al. 2021a; Ahmed et al. 2021c).

Based on the above arguments, the econometric model of this paper is constructed as follows:

$$\mathrm{EFP}^{it} = f\left(Y^{it}, Y^{2it}, \mathrm{EC}^{it}, \mathrm{RD}^{it}, \mathrm{FD}^{it}, \mathrm{DA}^{it}\right) \tag{1}$$

$$\mathrm{EFP}^{it} = \vartheta^{1} Y^{it} + \vartheta^{2} Y^{2it} + \vartheta^{3}\mathrm{EC}^{it} + \vartheta^{4}\mathrm{RD}^{it} + \vartheta^{5}\mathrm{FD}^{it} + \vartheta^{5}\mathrm{DA}^{it} + \varepsilon^{it} \tag{2}$$

where i denotes the cross sections, i.e., the UK, France, Germany, Japan, the USA, Italy, and Canada. The time is expressed by t, which is between 1985 and 2017. The $\vartheta' s$ represents coefficients, and ε denotes the error term. The variables' measurements and data sources are presented in Table 1. Furthermore, the economic complexity index and democratic accountability are plotted in Figs. 1 and 2, respectively. The period of this empirical investigation (1985 to 2017) depends upon the availability of data on democracy and EFP. The analysis chart for this research is depicted in Fig. 3.

Econometric techniques

Cross-sectional dependence

There are several concerns linked with panel data. Nonetheless, CD is a significant concern that should be considered before proceeding to further analysis. The inability to resolve the CD produces estimator and parameter with irrelevant results (Lobon et al. 2021; Ahmed et al. 2020b). From our point of view, we anticipate CD among the G7 countries since their markets are tightly connected, and as a result of economic association, G7 countries have similar characteristics.

Table 1 Data sources and unit of measurements (period of research = 1985 to 2017)

Indicators	Symbol	Unit of measurement	Source
Ecological footprint	EFP	Global hectares per capita	GFN (2020)
Economic growth	*Y*	GDP per capita constant 2010 US dollars	World Bank (2020)
Public budgets in renewable energy research development and demonstration	RD	Measured in per capita US dollars (2018 PPP)	IEA (2020)
Democratic accountability	DA	Democratic accountability index on the scale of 0 to 6 where 6 is the highest value. It is taken from the International Country Risk Guide	ICRG (2020)
Economic complexity	EC	Measure by economic complexity index	OEC (2020)
Financial development index	FD	The index on financial development is the ranking of nations based on access, depth, and efficiency of their financial markets and institutions	IMF (2020)

Investigators' compilation

A shock in any one of these economies can definitely affect the others. In this study, the popular Breusch-Pagan Lagrange multiplier (LM) and Pesaran scaled LM methods are utilized for CD analysis. The estimations show the existence of CD in our data.

Unit root testing

In unit root tests, first of all, the CIPS test is utilized. In addition, the paper relied on cross-sectionally augmented ADF and IPS tests developed by Pesaran (2007), which are commonly known as the cross-sectionally augmented Dickey-Fuller (CADF) and CIPS tests. The CADF test equation is given as follows:

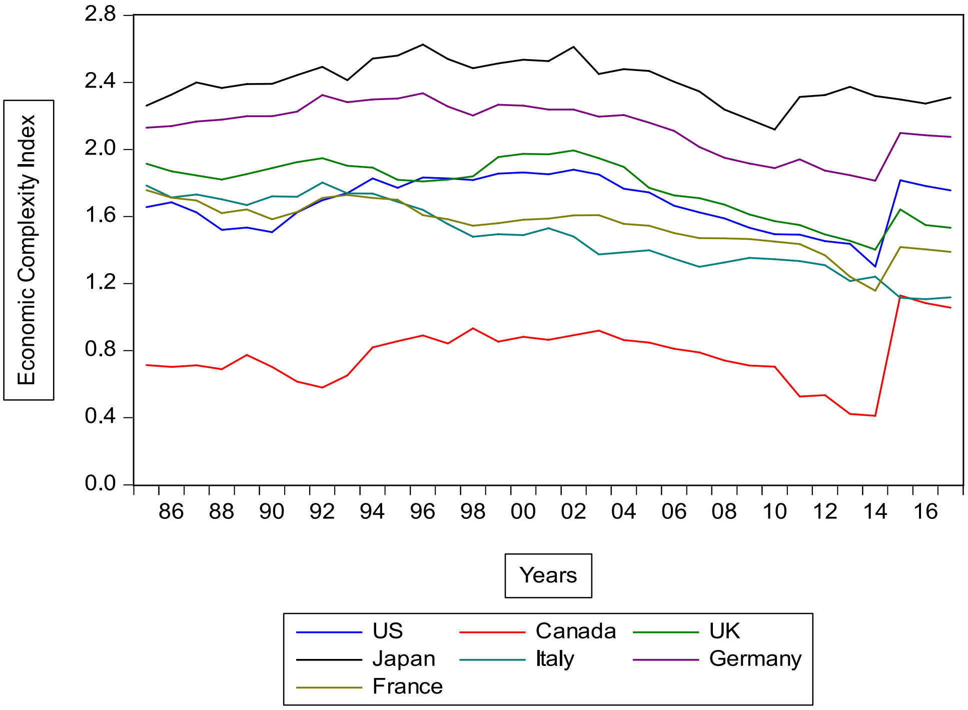
$$\Delta Y_{i,t} = \gamma_i + \gamma_i Y_{i,t-1} + \gamma_i \overline{X}_{t-1} + \sum_{l=0}^{p} \gamma_{il} \Delta \overline{Y_{t-l}} + \sum_{l=1}^{p} \gamma_{il} \Delta Y_{i,t-l} + \varepsilon_{it} \tag{3}$$

where $\overline{Y}_{t-1}$ and $\Delta\overline{Y_{t-l}}$ denote the lagged and first difference averages, respectively. Further, Eq. (6) shows the test statistic of CIPS which is attained by taking an average of individual CADF.

$$\widehat{\text{CIPS}} = \frac{1}{N} \sum_{i=1}^{n} \text{CADF}_i \tag{4}$$

where the CIPS in Eq. (4) is derived from Eq. (3). The null and alternative hypotheses indicate non-stationarity and stationarity, respectively. Recently, these

Fig. 1 Economic complexity index



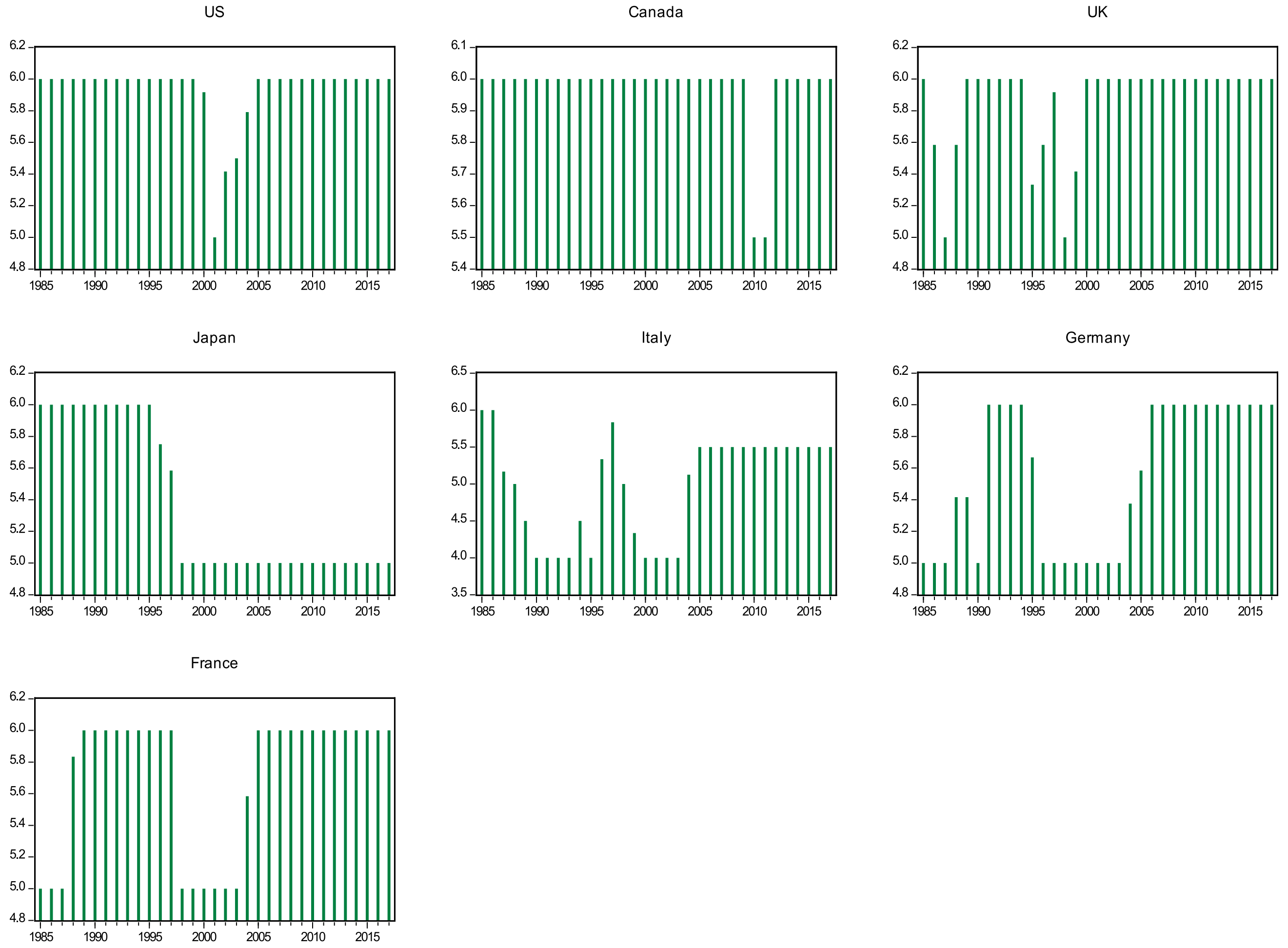


Fig. 2 Democratic accountability

second-generation tests have become very popular because the first-generation tests generate unreliable estimates, particularly if there is the presence of CD in the data.

Panel cointegration test

This study relied on the Westerlund (2007) cointegration method to determine the cointegration between EC, RD, DE, Y, Y^2, and EFP. Compared to other cointegration tests, for instance, Pedroni and Kao, the Westerlund test is more reliable. The test's general form is presented as follows:

$$G_t = \frac{1}{N}\sum_{i-1}^{N}\frac{\acute{\alpha}_i}{\mathrm{SE}\left(\acute{\alpha}_i\right)} \tag{5}$$

$$G_\alpha = \frac{1}{N}\sum_{i-1}^{N}\frac{\mathrm{T}\acute{\alpha}_i}{\acute{\alpha}_i(1)} \tag{6}$$

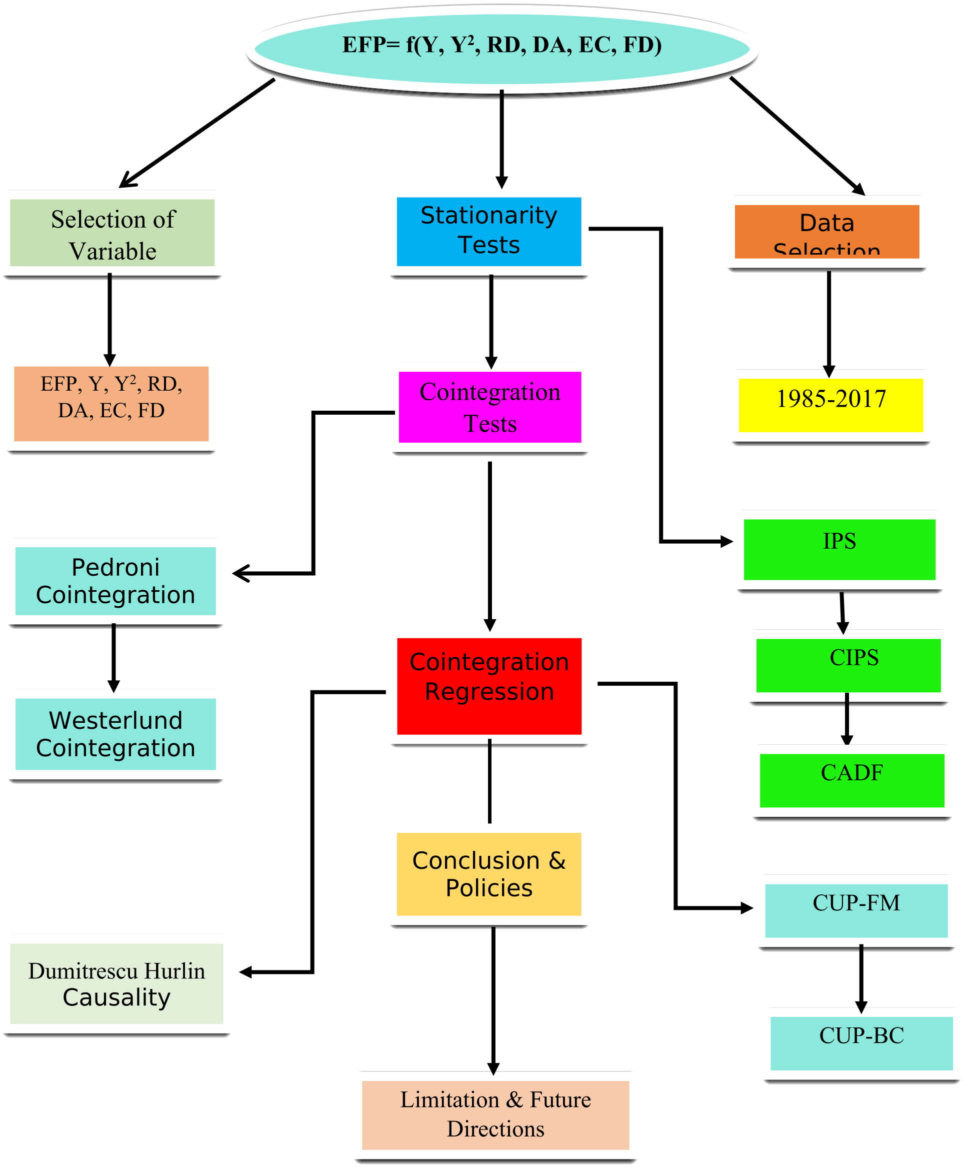
$$P_t = \frac{\acute{\alpha}}{\mathrm{SE}\left(\acute{\alpha}\right)} \tag{7}$$

$$P_\alpha = T\acute{\alpha} \tag{8}$$

where Eqs. (5) and (6) indicate the group mean statistics (G_a and G_t) and Eqs. (7) and (8) present the panel statistics (P_α and P_t).

This research also uses one of the most sophisticated cointegration tests suggested by Westerlund (2008) as a robustness check of the cointegration analysis. Centered on the Durbin-Hausman (DH) concept, this recent methodology incorporates two measures that can be utilized to analyze the nature of cointegration, i.e., DH group and DH panel tests. Even with stationary regressors, such tests are still applicable (Ahmeed et al. 2021; Olanrewaju et al. 2021; Beton Kalmaz and Adebayo 2020). This method has both null and alternative hypotheses of "no cointegration" and

Fig. 3 Flow chart



"cointegration," respectively. This advanced test computes reliable findings accounting for CD.

CUP-FM estimator

To capture the association between EFP and the regressors, the study followed Murshed (2020) and employed the CUP-FM estimator. The CUP-FM estimator is suggested by Bai et al. (2009) for panel data. We presume there is a panel trend as follows to implement this estimator.

$$y_{it} = x_{it}\beta + e_{it} i = 1, \dots .n, t = 1, \dots .T, X_{it} = X_{i,t-1} + \varepsilon_{it} \quad (9)$$

where the dependent variable is depicted by y_{it}, a set of k non-stationary regressors represented by X_{it}; β is a $k \times 1$ vector of slope indicators; and the error term is illustrated by ε_{it}. The least combined square estimator for β parameter is depicted as follows:

$$\hat{\beta}_{\mathrm{LS}} = \left(\sum_{i=1}^{n} \sum_{t-1}^{T} X'_{it} X_{it} \right)^{-1} \sum_{i=1}^{n} \sum_{t-1}^{T} X'_{it} y_{it} \quad (10)$$

In view of the Phillips and Hansen (1990) study, the border range of this estimator is moved away from zero attributed to the prevalence of bias between e_{it} and ε_{it}, unless X_{it} is exclusively exogenous in a circumstance. Thus, to accomplish long-term reliability and asymptotic normal distribution, the FMOLS estimator can be viewed as a Phillips and Hansen method for panel data. Also, the cross-sectional independent hypothesis in time-series research is too narrow and cannot probably be explained.

Bai et al. (2009) claimed that the equation error term and regression conform to the factor pattern of the following interaction for understanding cross-sectional dependence:

$$e_{it} = \lambda_{it}F_t + U_{it} \tag{11}$$

where F_t is an $r \times 1$ vector of common latent factors, and λ_i is an $r \times 1$ vector of factor weights; then, the pattern of the panel of interaction (2) can be illustrated as follows:

$$y_{it} = \acute{X}_{it}\beta + \acute{\lambda}_{it}F_t + u_{it} \tag{12}$$

The estimates can be strengthened by removing F_t from the error term and applying it to the regression function. If any of the X_{it} elements are stationary and F_t is associated with X_{it}, the β calculation would be contradictory regarding F_t as a component of the distortion term. The CUP-FM estimator, which offers a comprehensive approximation of the equation coefficients, is implemented and described as follows:

$$\hat{\beta}_{\text{CUP-FM}} = \left[\sum_{i=1}^{N} \acute{X}_i M_{\hat{F}} X_{it}\right]^{-1} \sum_{i=1}^{n} \left(\acute{X}_i M_{\hat{F}} y_i + -T\left(\hat{\Delta}+_{\varepsilon ui} - \hat{\delta}_i \hat{\Delta}+_{\eta u}\right)\right) \tag{13}$$

$$\widehat{FV}_{nt} = \left[\frac{1}{nT^2} \sum_{i=1}^{n} \left(y_i - X_i \widehat{\beta}_{\text{CUP-FM}}\right)\left(y_i - X_i \widehat{\beta}_{\text{CUP-FM}}\right)^{\iota}\right] \tag{14}$$

The parameter η is the process of autoregression distortion term of F_{t} and with assuming F_t non-stationary depicted below.

$$F_t = F_{t-1} + \eta_t \tag{15}$$

It is known that the relationship $u_{it} = a_i n_t + b_{it}$ occurs between the sentences (errors) of the distortion terms, in Eqs. (13) and (15). As a consequence of the frequent solution of two unknown $\widehat{\beta}_{\text{CUP-FM}}$ and $\widehat{F}$ in two in Eq. (15), the CUP-FM and CUP-BC methods utilized in this paper are considered to be reliable even during fractional integration, autocorrelation, CD, heteroscedasticity, endogeneity, etc.

Dumitrescu and Hurlin causality test

To analyze the causal nexus between CO_2 emissions and its regressors, the study employs the Dumitrescu and Hurlin causality test developed by Dumitrescu and Hurlin (2012). Whether T is greater or less than N, it is suitable to employ this test. In addition, for a heterogeneous and balanced panel data set, this method is valuable. Furthermore, this method can also treat the cross-sectional dependence issue. This test is presented in Eq. (16).

$$z_{i,t} = \alpha_i + \sum\nolimits_{j=1}^{p} \beta_i^j z_{i,t-j} + \sum\nolimits_{j=1}^{p} \gamma_i^j T_{i,t-j} \tag{16}$$

where j denotes the lag length and β^j (j) depicts the autoregressive parameters. The alternative and null hypotheses postulate causal association and no causal association, respectively.

Empirical findings and discussions

Descriptive statistics of variables presented in Table 2 show that democracy (DE) has a mean value of 5.62, which indicates that G7 countries have strong democratic accountability since the total index ranges between 0 and 6 and 6 is the maximum possible value of democratic accountability. Likewise, EC has an average of 1.68, and the maximum value of this index is 2.62, which is quite high because G7 countries are very advanced economies with sophisticated economic structures. Likewise, the mean value for EFP is about 6.37715, which is substantial, considering that the average available biocapacity per capita is 1.6. It infers that G7 nations have very high environmental footprints.

Moreover, in Table 3, EFP is positively correlated with most regressors and negatively correlated with EC. We also computed the variance inflation factor (VIF) values for all variables to assure that there is no multicollinearity in data. The estimates in Table 4 illustrate that VIF values are below 5; thus, there is no multicollinearity issue in the model.

Cross-sectional dependence and unit root outcomes

Before applying unit root tests, we scrutinized the CD using Breusch-Pagan LM and Pesaran CD and scaled LM tests, and the results (Table 5) disclose CD in our data in all tests. This is reasonable since G7 countries are strongly interlinked, and we must adopt a methodology robust against

Table 2 Descriptive statistics

	EFP	Y	RD	DE	EC	FD
Mean	6.37715	38,779.12	1.55981	5.62572	1.68501	0.70981
Median	5.52917	38,577.73	1.17047	6.00000	1.71064	0.74832
Maximum	10.4292	53,356.24	8.36283	6.00000	2.62482	0.93881
Minimum	4.20077	24,355.08	0.07968	4.00000	0.41136	0.38323
Std. Dev	1.81163	6288.950	1.29161	0.53709	0.50719	0.13605

Table 3 Correlation matrix

	EFP	Y	RD	DA	EC	FD
EFP	1					
Y	0.28717	1				
RD	0.02045	0.52968	1			
DA	0.34244	0.20897	0.00339	1		
EC	−0.46334	−0.19103	−0.14529	−0.25669	1	
FD	0.109472	0.71207	0.44772	0.17898	−0.03589	1

CD for the analysis. Thus, we opted for the famous CIPS and CADF tests to deal with this issue. Also, the IPS test was used for unit root analysis. The analysis in Table 6 indicated that all six variables became stationary at 1(1), while LNDE and LNEC were stationary at 1(0) in the CADF and CIPS methods. However, the results did not show any variable integrated at 1(2); hence, we can check cointegration.

Cointegration outcomes

The cointegration analysis is started by applying the traditional Pedroni test, and the outcomes in Table 7 depict cointegration since 5 statistics out of 7 are significant. This conclusion is also supported by the findings given in Table 8. The Pt and Gt statistics of the Westerlund (2007) methods are also substantial, which implies that analyzed variables move together in the long-run approach. This technique accounts for CD and is very popular in panel data analysis.

However, in the final step of cointegration analysis, we used the Westerlund (2008) test, which accounts for CD, and stationary regressors cannot affect its results. The DHp and DHb statistics are significant in Table 9, supporting our earlier conclusions. Based on these findings, we can conclude that the analyzed variables move together in the long-run approach.

Long-run estimation outcomes

The finding of cointegration leads us to use the CUP-FM long-run approach. The estimates obtained in Table 10 divulge that that EC alleviates EFP. More specifically, a 1% rise in EC decreases EFP by 0.00502, implying that the knowledge-based complex economic structure of G7 countries promotes environmental sustainability. This finding is in line with the results of Can and Gozgor (2017), who report that EC mitigates emissions in France, and Doğan et al. (2020), who reveal that EC subsidizes emissions in OECD countries.

Table 4 VIF analysis

Variable	VIF	1/VIF
Y	2.41	0.41471
FD	2.13	0.46992
RD	1.45	0.68827
DE	1.14	0.87951
EC	1.14	0.88085
Mean VIF	1.65	

The fresh evidence that EC alleviates EFP in G7 countries is reasonable since EC's impact on EFP may differ according to countries' development levels. According to Apergis et al. (2018), underdeveloped countries focus on specialization in agricultural products, and during this process, economic complexity and energy demand are usually low. When countries enter the developing group, they tend to focus on manufacturing more knowledge-based complexed products as compared to the agricultural stage (Can & Gozgor 2017; Yuping et al. 2021). However, in the quest to develop complex products, countries develop energy-intensive products, such as metal and cement (Hu et al. 2020). Hence, environmental deterioration can upsurge at this stage.

Nevertheless, when countries achieve significant economic development (as in our case), they start dumping resource-intensive products from their production basket. Generally, with more development, society shifts its preference from economic development to environmental sustainability. It develops more knowledge-based complex products that need less energy and other manufacturing resources (Doğan et al. 2019). Therefore, in highly developed G7 countries, EC reduces ecological footprint.

The coefficient of democracy in Table 10 is also significant, denoting that democracy (DA) does not reduce EFP. Instead, it intensifies EFP, i.e., a 1% surge in DA results in a 0.0387% rise in EFP. This result is surprising, and it opposes the conclusions of Lv (2017) and Adams and Acheampong (2019) that DA alleviates emissions in emerging countries and Africa, respectively. Nevertheless, Wang et al. (2018), who disclose that DA is a major contributor to worsening air quality in G20 nations, somewhat support our finding. They argue that the effectiveness of democracy in improving the environment can only be seen in immature economies where democracy helps improve the overall management and institutional quality. However, the

Table 5 Cross-sectional dependence

	EFP	Y	Y^2	RD	DE	NEC	FD
Breusch-Pagan LM	242.7866* (0.0000)	309.0340* (0.0000)	309.9659* (0.0000)	138.2778* (0.0000)	98.4050* (0.0000)	142.9742* (0.0000)	151.3528* (0.0000)
Pesaran scaled LM	34.2224* (0.0000)	44.4446* (0.0000)	44.5889* (0.0000)	18.0963* (0.0000)	11.9438* (0.0000)	18.8210* (0.0000)	20.1139* (0.0000)
Pesaran scaled CD	14.9475* (0.0000)	9.2894* (0.0010)	3.1759* (0.0015)	10.3159* (0.0000)	5.3351* (0.0000)	10.0401* (0.0000)	7.4862* (0.0000)

*One percent significance level

conflict between sustainability and economic development at a high development level forces democracies to opt for development, which increases environmental degradation. Interestingly, the US withdrawal from the Paris Agreement is one example of this conflict where a democracy opted for development (Ahmed et al. 2021b, d). This outcome is also in consonance with the notion of modernization theory that improvement in democracy nurtures economic development, which intensifies environmental degradation (Heilbronner 1974; Roberts & Parks 2008; Usman et al. 2019).

The coefficients of Y and Y^2 (−0.0089 and 0.0072) are significant, suggesting that EF will increase with more development. This outcome corroborates the idea of a U-shaped link between income (economic growth) and EFP disclosed by Destek and Sarkodie (2019) for India, Turkey, China, South Korea, and Thailand. This evidence is also supported by Destek et al. (2018) for developed EU countries and Sarkodie (2018) for African nations. The fresh finding denotes that the conflict between economic growth and the environment will force G7 countries to opt for development at the cost of environmental sustainability; thus, the EKC is invalid when accounting for economic complexity, democracy, and renewable energy budgets. Currently, the income level of these developed countries supports environmental sustainability, but with an upsurge in income level, stress on natural resources associated with rising human demands will intensify resource consumption, and consequently, EFP will increase. The result highlights that economic development in G7 is leading towards environmental unsustainability and immediate policies are necessary to attain sustainability. RD's effect (renewable energy technology budgets) on EFP is also significant and negative, upholding the notion that RD contributes to supporting environmental sustainability. A rise of 1% in RD can help attain a 0.0406 reduction in EFP. This result contradicts the claims of Garrone and Grilli (2010) and Koçak and Ulucak (2019) that RD does not alleviate emissions in the OECD and some major economies, respectively. However, Alvarez-Herranz et al. (2017) and Jin et al. (2017) support this result as they noticed a decline in emissions because of energy budgets in the OECD and China, respectively. This mitigating effect is not a surprise because public sector renewable energy technology budgets can play a vital role in developing green energy technologies (Ardito et al. 2019), which help replace pollutant energy sources with green energy.

Lastly, FD's coefficient (financial development) is negative, and its significance suggests that FD alleviates EFP. The financial development index used in the study categorizes countries based on efficiency, access, and depth of their financial market and financial intuitions; hence, this makes our outcome different from many previous studies. The finding is in line with Uddin et al. (2017) and Ahmed et al. (2019) for 27 nations and Malaysia, respectively. The nature of lending determines the role of FD. For example, lending money to projects involving research

Table 6 Unit root tests

Variable	IPS		CIPS		CADF	
	Level	First differences	Level	First differences	Level	First Difference
EFP	0.81793 [0.7933]	−3.33280* [0.0004]	−2.233	−5.576*	−2.708	−4.414*
Y	−0.61403 [0.2696]	−3.07493* [0.0011]	−2.241	−2.937**	−2.241	−3.059**
RD	−0.90191 [0.1836]	−1.9920** [0.0228]	−3.439*	−5.815*	−3.022*	−4.396*
DA	−1.31995*** [0.0934]	−3.27885* [0.0005]	−3.154*	−4.746*	−3.977*	−4.014*
EC	−0.58430 [0.2795]	−2.44420* [0.0073]	−2.103	−5.183*	−2.490	−3.248*
FD	−2.31142 [0.9896]	−3.42698* [0.0003]	−2.220	−5.977*	−2.199	−4.061*

CADF and CIPS test critical values are as follows: 1% (−3.060), 5% (−2.84), and 10% (−2.73). Prob. values are in brackets for the IPS test. For the CADF test, T-bar value is reported

*One percent significance level

Table 7 Pedroni cointegration test

	Stat	Prob	Weighted stat	Prob
Common AR coefs. (within-dimension)				
Panel v stat	4.52698*	0.0000	4.545372*	0.0000
Panel rho stat	2.01823	0.9782	2.002995	0.9774
Panel PP stat	−6.22113*	0.0000	−5.811898*	0.0000
Panel ADF stat	−3.82650*	0.0001	−3.768341*	0.0001
Individual AR coefs. (between-dimension)				
Group rho stat	2.485587	0.9935		
Group PP stat	−7.763812*	0.0000		
Group ADF stat	−2.874164*	0.0020		

Individual intercept and trend option are used to compute results

*One percent significance level

and development in efficient green technology and investment in the agriculture sector can reduce EFP (Ahmed et al. 2021c). The results imply that in G7 countries, financial development supports research and development and green technology manufacturing resulting in a reduction in EFP.

In the next step, the study employed the CUP-BC method to validate our long-run findings. The estimates in Table 10 are enormously consistent with the CUP-BC results. For instance, the coefficients for DA and Y^2 are positive, while all other coefficients (Y, EC, FD, RD) are negative. The results are also significant, hence validating the findings of this study. The results are also presented in Fig. 4.

Dumitrescu and Hurlin causality test outcomes

Lastly, the DH causality approach showed that in Table 11, EC Granger causes EFP. Likewise, democracy (DA) also causes EFP. Causality also runs from our other regressors (Y, Y^2, RD, and FD) to EFP. These causal directions specify that policymakers can influence EFP in G7 countries by designing policies on variables analyzed in this study. Cleaner energy budgets (Granger) cause Y with feedback inferring that renewable energy budgets are critical for increasing income, and an increase in income also helps allocate funds for RD. Likewise, there is a feedback effect between EC and RD, implying that structural transformation in G7 countries influences RD. At the same time, the latter also influences the manufacturing of complex products. Results also unveil causality from FD to income and economic complexity, which highlights the role of financial development in structural transformation and economic development. Figure 4 illustrates the key outcomes of the empirical analysis.

Table 8 Westerlund (2007) test for cointegration

Stats	Value	*Z* value	*P* value	Robust *P* value
Gt	−3.962**	−2.257	0.012	0.023
Ga	−11.922	2.545	0.995	0.188
Pt	−9.893**	−2.089	0.018	0.025
Pa	−12.114	1.534	0.938	0.153

Four hundred replications are used for bootstrapping

**Five percent significance level

Table 9 Westerlund (2008) cointegration test

		Prob
DHg	−2.037**	0.021
DHp	−1.688**	0.046

**Five percent significance level

Conclusion and policy directions

As a proxy of environmental degradation, the EFP has taken enormous attention from academics, policymakers, and researchers in the contemporary literature. Although the effect of energy use and economic growth on EFP has been extensively investigated, there is no large body of literature focusing on the effects of economic complexity, RD, and democratic accountability on EFP for the case of the G7 countries. Therefore, the possible impacts of economic complexity, RD, and democratic accountability for ensuring environmental sustainability in the G7 countries remain a puzzle. Against this milieu, the current study is likely to assist in the formulation of relevant environmental policies to safeguard and reinstate environmental well-being in these highly developed countries. The findings from this present study reveal that (i) the combination of economic complexity, RD, democracy, financial development, and economic growth significantly affects the long-run pattern of the EFP figures in the G7 countries;

Table 10 Long-run estimations

Variables	Long-run results CUP-FM		Robustness analysis CUP-BC	
	Coefficients	T stats	Coefficients	T stats
Y	−0.00892	−22.04381*	−0.00997	−21.62093*
Y^2	0.00728	23.52459*	0.01058	30.11957*
RD	−0.04067	−91.25103*	−0.04277	−90.10082*
DA	0.03871	61.84560*	0.04839	70.59892*
EC	−0.00502	−10.61548*	−0.00393	−7.19899*
FD	−0.02085	−42.90446*	−0.02123	−39.20863*

*One percent significance level

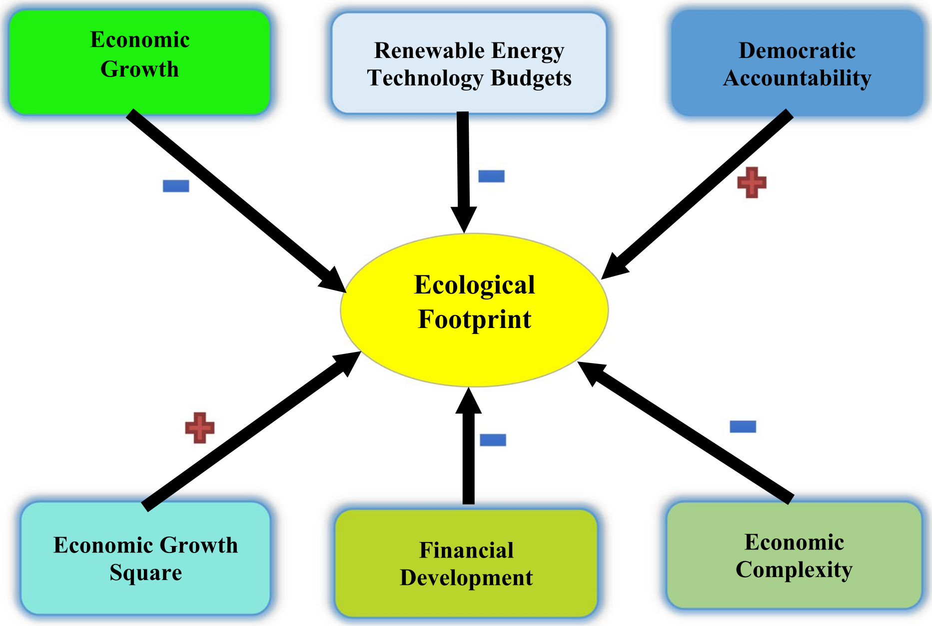


Fig. 4 Key findings from CUP-FM and CUP-BC

(ii) astonishingly, democracy in the G7 countries do not help reduce EFP; rather, it increases environmental degradation; (iii) economic complexity, RD, and financial development mitigate EFP; and (iv) the economic growth-EFP relationship depicts a U-shaped linkage. Based on these key findings, the following policy suggestions are proposed:

- Firstly, since economic growth is witnessed to intensify the EFP in the G7 countries, this would be a major issue that needs to be addressed by redesigning the economic development policies in line with the environmental sustainability objectives. The implementation of such policies will pave the way towards greater use of clean energy within the production processes and, therefore, phase out the fossil fuel dependency of the G7 nations as well. It is pertinent for these economies to prioritize the attainment of environmental welfare to sustain their economic achievements in the future. In this regard, the governments of the G7 countries should ideally encourage private investments in green initiatives which would not only help facilitate economic growth but would also restore environmental well-being in tandem.
- Secondly, since democratic accountability is not found to facilitate environmental development in the G7 countries, it implicates that the people of these countries are not exercising their democratic rights to pressurize the government in safeguarding the environmental attributes. Hence, it is critically important to enhance environmental awareness among these people. Once the people would get accustomed to the multidimensional adversities associated with environmental degradation, the general public may pressurize their political leaders to allocate more budgets for cleaner energy development and to simultaneously implement stringent ecological regulations. Consequently, enhancing democratic accountability can be expected to protect ecological interests, which, in turn, could ideally reduce the EFP of the G7 countries. In this regard, ensuring social awareness is said to play a key role in negating the adverse environmental impacts associated with democracy in the G7 context. This can be done through public investments in the education sector, especially to create environmental awareness within these countries.
- Thirdly, the degrees of economic complexity in the G7 countries should be enhanced further to attain the environmental development objectives. In this regard, the G7 countries should add certain commodities in their respective export baskets, particularly products that are relatively less resource-intensive and can be produced by utilizing cleaner resources. Simultaneously, the level of RD should also be enhanced since it would not only help enhance the economic complexity level of the G7 countries but would, more importantly, reduce the energy intensity levels and promote clean energy transition. Besides, the recent literature has also acknowledged the roles of investment in technological development for clean energy transition purposes. Thus, enhancing RD can be expected to boost renewable and nuclear energy use in the G7 countries which, in turn, could be effective in mitigating the environmental hardships further. As a result, it can be said that economic complexity and RD

Table 11 Dumitrescu and Hurlin test

Path of causality	Zbar stat	Prob
Y→EFP	10.0089*	0.0000
EFP→Y	−0.30565	0.7599
RD→EFP	5.64535*	0.0000
EFP→RD	0.50641	0.6126
DA→EFP	1.90049***	0.0574
EFP→DE	−0.27172	0.7858
EC→EFP	3.97337*	0.0000
EFP→EC	0.67787	0.4979
FD→EFP	2.40116**	0.0163
EFP→FD	0.08804	0.9298
RD→Y	2.21828**	0.0265
Y→RD	9.42310*	0.0000
DA→Y	−0.10095	0.9196
Y→DE	0.82835	0.4075
EC→Y	−0.76347	0.4452
Y→EC	0.36464	0.7154
FD→Y	8.00852*	0.0000
Y→FD	−0.33073	0.7408
DA→RD	0.29363	0.7690
RD→DA	0.69162	0.4892
EC→RD	3.27080*	0.0011
RD→EC	1.96628**	0.0493
FD→RD	9.56631*	0.0000
RD→FD	−0.63319	0.5266
EC→DA	0.73496	0.4624
DA→EC	0.76240	0.4458
FD→DA	−0.13853	0.8898
DA→FD	0.55876	0.5763
FD→EC	2.23168**	0.0256
EC→FD	−1.29588	0.1950

*One percent significance level

**Five percent significance level

***Ten percent significance level

can jointly contribute to restoring environmental well-being in these countries of concern.

Lastly, the G7 countries should also aim at further developing their financial sectors particularly through ensuring greater access to green finance for the private investors. This would not only boost the local investment levels to stimulate economic growth in these countries, but also facilitate investments in cleaner production processes to ensure complementarity between economic and environmental welfare. At the same time, preferential interest rate arrangements should be introduced whereby the loans for financing of green projects could be availed at a relatively lower cost compared to the costs of borrowing money for environmentally unfriendly production purposes.

Due to the unavailability of data beyond 2017, we had to limit our study period from 1985 to 2017. This is the only limitation experienced in conducting this study. As part of the future scope of research, this study can be extended to perform a disaggregated analysis by assessing the impacts of the explanatory variables on the different components of the aggregate EFP figures of the G7 countries.

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