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Analyzing transport demand and environmental degradation: the case of G-7 countries

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Abstract
The debate for green development has been ongoing in the energy and environment literature—especially initiatives to mitigate climate change. On this note, we explore the effects of the air and railway transport demand, fossil-fuel energy consumption, demographic policies, economic growth, and alternative energy consumption on environmental degradation in Group of Seven (G7) economies. Using robust panel estimation techniques that account for cross-sectional dependence, empirical results affirm the presence of long-run relationships among variables. Besides, the results give credence to the environmental Kuznets curve hypothesis (EKC) in G7 countries over the sampled period. We observe that demand for air transport, energy from fossil fuel sources, and economic development dampen environmental quality by 0.12%, 0.33%, and 46.54%, respectively. Interestingly, renewable energy and rail transportation demand improve environmental quality. This outcome resonates with the need for alternative and clean energy production and consumption (Sustainable Development Goals 11 and 12) while enhancing the fight against climate change—especially the adoption of clean energy technologies in the air transport sector for sustainable growth.

Keywords Ecological footprint · Heterogeneous effects · Air transport · Railway transport · EKC hypothesis · Panel data modeling

JEL Classification Q56 · R4

1 Introduction

Due to global concerns about environmental degradation and anthropogenic emissions, the last decade has witnessed an unprecedented increase in ecological research. As a result of the hazardous level environmental degradation has reached today, many scholars have performed different studies assessing various factors including economic development (Aslan & Gozbasi, 2016; Mikayilov et al., 2018; Adedoyin et al., 2019), tourist activities (Khan

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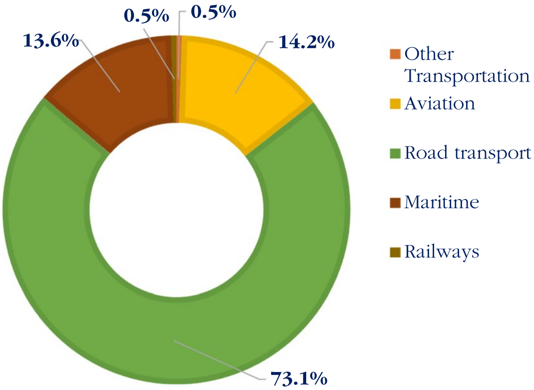

Fig. 1 GHG emissions from the transportation sector. Data source: European Union Transport system, 2019 [https://buff.ly/3zGKVLl]

et al., 2018), environmental Kuznets curve (EKC) hypothesis (Esteve & Tamarit, 2012; Aslan & Gozbasi, 2016), renewable/fossil energy consumption (Dogan & Ozturk, 2017; Esso, 2010; Esso & Keho, 2016), which either upsurge or decline emissions. These studies were conducted to highlight the policy direction on reducing global anthropogenic emissions. According to the United Nations Global Climate Change Report (2019), the current century is characterized by rising record levels of environmental degradation and emission, thereby leading to toxic impacts on environmental quality. This means updating policy directions requires consistent action; thus, assessing the linkage between travel demand, energy consumption, and environmental degradation while introducing democracy and the Kuznets hypothesis is necessary for environmental policy development.

Land (i.e., road and railway), sea, and air transport systems contribute significantly to the global economy—nonetheless amount to the emanation of toxic substances such as carbon dioxide emissions, methane, and others. According to the 2019 European Union for Climate Action report, transportation is the major cause of pollution in European cities—accounting for one-quarter of total greenhouse gas (GHG) emissions. As revealed in Fig. 1, various forms of transportation drive GHG emissions. Road transportation is the major contributor to GHG emissions—accounting for 73.1%, followed by aviation or air transport—accounting for 14.2% of total GHG emissions. Fossil fuel by-products from the aircraft business are riskier than other means of transport activities—because it mutilates the arrangement of climate at a high range while compounding GHG substance fixation at the surface climate. Thus, air transport increases the toxicity of anthropogenic emissions, increasing environmental pollution. Besides, Chapman (2007) reported that the 1997 Kyoto Protocol caused a decline in global anthropogenic emissions in the airline industry.

Since the discharges from transportation present enormous danger to the environment and sustained economic growth, the transport–emission nexus cannot be ignored—due to its role in economic development. Consequently, the environmental policy requires more firm procedures and strategies to control the transport–emission nexus (Ouyang et al., 2019). Hence, Grossman and Krueger (1995) re-explained the Kuznets curve (KC) hypothesis proposed by Simon Kuznets (1955). According to this hypothesis, an inverted U-shaped association exists between economic growth per capita and income inequality. This implies economic growth and income inequality simultaneously rise until a certain level—where the economy continues to increase as income inequality begins to decline.

However, due to the continuous rise in global environmental issues, Grossman and Krueger (1995) reinterpreted the curve as environmental Kuznets curve (EKC) hypothesis—which explains the inverted U-shaped relationship between the environmental pressure and income per capita growth. According to the EKC hypothesis, income per capita and ecological degradation increase when income growth reaches a threshold—where environmental degradation decreases thereafter. Stern (2014) argues that the factors of environmental emissions tend to worsen due to advancement in economic development until a threshold of income level is achieved. The EKC hypothesis is a helpful tool for combating climatic problems caused by GHG emissions (Sarkodie & Strezov, 2019). Thus, several empirical studies examine the validity of the hypothesis (Esteve & Tamarit, 2012; Aslan & Gozbasi, 2016), and researchers employed several indicators of environmental degradation levels such as sources of energy, demographic indicators, technology, and source of economic activity. (Sinha et al., 2019). However, less attention has been paid to investigate the role of transport activities on environmental quality. A limited number of studies investigated the role of transport activities on environmental degradation.

This study questions *"how transportation activities interact with the environment in G-7 countries"*. Understanding the nature of the nexus between transportation choices and the environment can help establish sustainable transport policies while achieving the environmental and transportation aim of the SDGs. To the best of our knowledge, this paper first investigates which transport choices are more sustainable in G-7 countries. Therefore, studying the effect of transportation activities on the environment could provide deep insights for decision-makers to establish efficient transportation policies that may help G-7 countries in fulfilling responsibilities arising from international environmental diplomacy. Moreover, understanding the nature of the effect of transport choices could help policymakers and consumer behaviors in the long-run and migrate toward eco-friendly consumption patterns. Second, we contribute to the existing literature by controlling omitted-variable bias. Hence, we assess the effect of airline and railway transport demand alongside traditional variables such as income, fossil fuels, and renewables on environmental degradation. Besides, we incorporate democracy as the new factor to assess the role of institutional quality in long-term emission reduction. The democratic system of governance may allow citizens to demand environmental quality. Democratization or good institutional quality has social benefits/problems associated with governments' systems of operation (Akalin & Erdogan, 2021). Third, contrary to the adoption of carbon dioxide (CO_2) emissions in existing literature, we use ecological footprint (EF)—a more comprehensive indicator that captures several dimensions of environmental accounting to assess long-term degradation effects. Ecological footprint captures the whole impact of human activities on the environmental quality; it is required to consider multidimensional proxies of degradation (Dasgupta et al., 2002; Kaika and Zervas, 2013; Gill et al., 2018), so that genuine deterioration that adversely affects the ecosystem and sustainable development would be comprehensively measured. For this purpose, EF proposed by Wackernagel and Rees (1996) is taken as an alternative for CO_2 emissions in the context of the EKC hypothesis. Fourth, we adopt novel estimation methods that account for common global shocks, transboundary effects, and heterogeneous effects. Accounting for such panel characteristics in the empirical model produces robust estimates useful for policy formulation. Therefore, this paper provides three distinctive contributions to the extant literature on the theme, sample, and method.

The rest of the paper is organized as follows: Section 2 summarizes existing literature, whereas Sect. 3 describes the data, and methodology and provides empirical results. Section 4 includes a discussion of the empirical results. Finally, Sect. 5 presents the conclusion with policy recommendations.

2 Literature review

2.1 The air transport-induced–emissions nexus

Burning a large percentage of oil is caused by the transport sector, one of the significant worldwide energy consumers. This prompts the creation and discharge of carbon dioxide and other ozone-depleting substances that may alter the climate, prompting environmental change. Moreover, Rashid Khan et al. (2007) argued that the appropriate function of the air transport system involves the utilization of a large amount of energy, thereby causing anthropogenic GHG emissions that affect environmental quality. The energy burned from transportation can be linked to travel demand among countries, thus leading to tourism and tourist activities. So, reviewing the empirical studies on tourism and emissions is tantamount to reviewing the transport–emission nexus. In lieu of this, several researchers have examined the transport–emission nexus while suggesting possible ways of reducing emissions. For instance, Abdallah et al. (2013) revealed a bidirectional relationship between transport and carbon emissions—implying CO_2 significantly impacts transport, whereas transportation causes CO_2 emission. The overall effect of carbon emissions on the environment affects air pollution while reducing economic growth because of spending required to reduce long-term pollution effects. Further research conducted by Gössling et al. (2015) revealed increasing demand for air transport contributed to an upsurge in global climate change from the airline sector. Thus, air travel contributes majorly to increasing ecological degradation[1]—due to the overdependence of the aviation sector on fossil fuels.

2.2 Democracy, institutional quality, and environmental quality nexus

The relationship between democracy and environmental quality is a widely debatable issue among scholars. Existing literature shows the role of democracy in reducing environmental degradation; however, others assume democracy harms ecological quality. This section, thus, presents the different theoretical and empirical arguments for the democracy–emission relationship.

According to Payne (1995), the cause of environmental interest groups that leads to public awareness and gathering support for environmental enactment is encouraged by the opportunity for individuals to exercise political rights and freedom of information. This works through public opinions on environmental issues. Thus, information on ecological issues streams more openly, and political rights are more preferably ensured in a vote-based system over totalitarianism. Additionally, Magnani (2000) proposes that property rights, democracies, and regard for basic liberties can create synergies that lead to expanded levels and adequacy of environmental strategy.

Ecological gatherings are frequently more fruitful at educating individuals and coordinating them to follow up on environmental issues in a democracy than in a despotism (Schultz & Crockett, 1990). Another argument is that institutional quality may likely promote environmental quality in a democratic system of governance than in an autocratic system. This is because democracies are bound to follow environmental arrangements since they regard the standard of law, thus raising ecological quality (Weiss & Jacobsen, 1999). According to Berge (1994), an economic opportunity is regarded by democracies;

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[1] The toxic effects of fossil fuels have long-term environmental consequences.

therefore, market economies promote environmental quality. Gleditsch and Sverdrup (2003) propose that as vote-based systems regard human existence more than despotism, they are more receptive to perilous ecological debasement. Likewise, vote-based systems participate in fewer wars and have a more significant environmental quality since wars obliterate the climate.

Several components rely on the view that environmental degradation may or may not lessen by democracies. Hardin (1968) cautions about the approaching danger of unchecked and ecological mismanagement without support from concerned policymakers. When private property privileges of regular assets are not well-defined, people or environmental groups tend to overuse such resources and overlook the harm that economic activities incur on the climate. Additionally, Paehlke (1996: 28) argues that the global economy and climate pose extraordinary peril for democracy and the environment. This is because the functionality of democracy is based on national levels; thus, global policy directions on environmental issues may not be topical for discussion in time. Heilbronner (1974) contends that the increase in global population growth contributes to the menace of environmental degradation. However, since democracies respect citizens' right to live and reproduce, imposing action to curtail human multiplication will be difficult, unlike autocracies, whose leaders are autonomous decision-makers.

Where ecological corruption is concerned, democracies regularly experience public strategy inaction. Democratic leaders tend to please the contending interest parties in the public to win votes (Midlarsky, 1998). Also, there can be a long-time argument between corporates and environmental groups, thereby ignoring a democratic decision on the action that will advance environmental quality. Spending limitations may hinder government responsiveness to ecological imperatives—but to additional major problems of financial means of significant parts of the democratic public (Midlarsky, 1998: 159). Moreover, democracies are hesitant to ease natural corruption since specific gatherings rely more on profit (or loss) from ecological strategies (Midlarsky, 1998: 159).

The environmental degradation and democracy nexus has long-term been an inconclusive subject of controversies among economists, political theorists, natural resource management studies, and social geography. Some scholars refuse to admit that the importance of democracy does not explain environmental disruption. Roberts and Parks (2007) modeled democracy as a determinant of environmental pollution, proxied by CO_2 emission, and found democracy has no significant effects on CO_2 emission. Scruggs (1998) used three different environmental proxies while controlling for economic inequalities and found no significant relation with democracy. Ahmed et al. (2022) revealed that democracy negatively affects ecological sustainability by employing a novel augmented ARDL method. Among scholars who show significant associations between democratic levels and environmental quality are Payne (1995), Barrett and Graddy (2000), Farzin and Bond (2006), and Torras and Boyce (1998). These scholars admit that people are more resilient in seeking environmental quality in a democratic system because of early warnings and ecological awareness, hence becoming more receptive to requests for environmental protection.

2.3 Other determinants of environmental quality

The main policy objectives of global communities are to control the toxic impact of environmental change and lessen global GHG emissions. This responsibility relies more on major polluters of CO_2 to meet specific emission targets outlined in the Kyoto Protocol and Paris Agreement. Thus, understanding the fundamental emissions factors is helpful in developing policy-oriented toward climate change reduction. Because of the apparent effects of environmental change on economic development and quality of life, several studies for decades have investigated the connection between ecological degradation, economic factors (such as GDP, EKC hypothesis, FDI, and travel demand), political factors, institutional factors, and energy consumption. For instance, Yoo (2006) found a two-way causal link between the consumption of coal rents and economic growth. This validates a mutual effect between economic growth and coal consumption. Thus, as economic growth booms, more coal resources are exploited and consumed, disrupting air quality. Also, Li and Li (2011) found a one-directional causal link from GDP per capita to coal consumption in selected countries, whereas the opposite effect was confirmed in other countries. In both scenarios, the GDP and coal consumption relationship degrade environmental quality, demonstrating a similar study by Apergis and Payne (2010).

Interest in improving economic growth and social investment has soared over the decades. Still, the increment without sustainability would require burning more fossil fuels, thereby releasing CO_2, a significant cause of GHG emissions that leads to climate change. This mystery brought the EKC theory that examines the relationship between economic growth (GDP per capita) and GHG emissions. For instance, Bagliani et al. (2008) revealed that the increase in economic growth does not affect environmental degradation. The same result is confirmed in Caviglia-Harris et al. (2009) and Wang et al. (2013). In another case study, Odhiambo (2012) averred the existence of a one-way causal relationship from GDP per capita to carbon emission, whereas energy consumption predicts emissions and economic development. This statement means economic productivity spurs emissions, but a feedback effect is observed between energy consumption and emissions.

Similarly, energy is needed for economic development, increasing energy demand as economic activities overgrow. In contrast, a study with a panel of Organization for Economic Co-operation and Development (OECD) and non-OECD countries revealed that while emissions underpin economic productivity in OECD countries, emissions do not trigger economic growth in non-OECD countries (Dinda, 2009). Several studies in Table 1 have assessed the validity of the EKC hypothesis—which explains an inverse U-shaped relationship between economic growth and emissions. The empirical review in Table 1 is an investigation of different proxies of environmental degradation and income. The last column of Table 1 shows the inconclusive validity of the EKC framework across several studies. It is observed that the same countries and regions show disparities in empirical results, showing the complexity of the EKC hypothesis. For instance, Ajmi et al. (2015) and Ari and Senturk (2020) find no evidence of the EKC hypothesis for G-7 countries, whereas Nabaee et al. (2015), Raza and Shah (2018), and Wang et al. (2020) support the validity of the EKC hypothesis. Contrary, Shahbaz et al. (2017) found mixed results of the EKC hypothesis across selected countries.

3 Data, methodology, and empirical results

3.1 Data and methodology

The economic development–environmental quality nexus has long been a significant discussion for policymakers and researchers since the original study of Grossman and Krueger (1991). The model specification became one of the considerable pathways in subsequent empirical studies. On the one hand, researchers have focused on the issue of the

Table 1 Validity of the EKC hypothesis

S/N	Authors	Country	Methods	Validity of EKC
1	Halicioglu (2009)	Turkey	ADF, ARDL, VECM causality	No EKC
2	Nasir and Rehman (2011)	Pakistan	ADF, PP, Johansen cointegration	EKC
3	Jalil and Faridun (2011)	BRIC	LLC, IPS, ADF, PP, OLS, VECM	EKC
4	Ajmi et al. (2015)	G7	Time-varying Granger causality analysis	No EKC
5	Nabaee et al., (2015	G7	Panel cointegration tests	EKC
6	Shahbaz et al. (2017)	G7	Nonparametric time series	Mixed
7	Raza and Shah (2018)	G7	FMOLS, DOLS, FE-OLS	EKC
8	Anser et al. (2020)	G7	Panel random effects,	EKC
9	Ari and Senturk (2020)	G7	Panel cointegration tests and long-term estimators	No EKC
10	Wang et al. (2020)	G7	Dynamic seemingly unrelated regression	EKC
11	Ahmad et al. (2021)	G7	CS-ARDL	EKC
12	Pata and Caglar (2021)	China	Augmented ARDL	No EKC
13	Qin et al. (2021)	G7	CS- ARDL	EKC
14	Balsalobre-Lorente et al. (2021)	EU-5	Panel cointegration tests, FMOLS	EKC
15	Frodyma et al. (2022)	EU	ARDL-bounds testing	No EKC
16	Çakar et al. (2022)	G7	Panel threshold regression	No EKC
17	Doğan et al. (2022)	G7	Panel cointegration tests, FMOLS, DOLS	EKC
18	Zhao et al. (2022)	G7	CCEMG, AMG	EKC
19	Miao et al. (2022)	NICs	Method of moments quantile regression (MMQR)	EKC
20	Zhao et al. (2022)	G7	CS-ARDL	EKC

choice of proxy variables for environmental degradation. Grossman and Krueger (1991) employed carbon emissions per capita as an indicator of environmental pollution; hence, many studies adopted a similar modeling strategy. However, the adoption of carbon emissions per capita has been criticized because of its one-dimensional environmental degradation tendency (Destek et al., 2018; Erdogan & Okumus, 2021). Contrary, some studies have since utilized the ecological footprint per capita proposed by Wackernagel and Rees (1998) because of its embracive proxy of environmental pollution (Solarin, 2019). Ulucak and Lin (2017) asserted that ecological footprint considers anthropogenic pressure on the environmental system on six sub-components, including footprints of carbon, forest, grazing land, cropland, fishing ground, and built-up land. Therefore, it could be regarded as a multidimensional indicator of environmental pollution compared to CO_2 emissions.

On the other hand, Grossman and Krueger (1991) employed international trade to increase the robustness of the EKC model, and international trade has become one of the significant parts of the empirical models. Afterward, sub-components of energy consumption have been integrated into empirical models. Energy-related regressors are essential parts of modeling environmental pollution because energy is considered the main driver of environmental deterioration (Sinha et al., 2019).

Furthermore, Hillman and Ursprung (1992) emphasized that the political system influences environmental performance. Median voters directly express their policy choice in direct democracies, which hinders policymakers from adopting discretion-based ecological policies. Contrary, policymakers can adopt environmental policies against the majority of voters in representative democracies, and monitoring discretion-based ecological procedures could be difficult for voters because of the principal–agent problem. In such a case, interest groups could use the lack of effective monitoring. Hence, governments may take environmental to please lobbying groups instead of the best interests of voters (Akalin & Erdogan, 2021; Dryzek, 1987; Olson, 1982). Besides, autocratic governments may object to enfranchising the demands of lobbying groups on ecological issues and prioritize public interest over lobbying groups. Thus, autocratic regimes can perform better in implementing international-based environmental commitments because of long administration terms (Bernauer & Koubi, 2009). Moreover, individuals have a greater opportunity to have information on environmental policies and freely express their policy choices in democracies than in autocracies. In this manner, individuals can put political pressure on politicians by using democratic institutions to have a cleaner and more sustainable environment (Acemoglu & Robinson, 2006).

A significant segment of the former studies used economic activity-based indicators, including industrial and agricultural production, energy production, transportation activities, and forestry. Transportation activities ease the mobility of labor, goods, and services—strengthen competition and market mechanism—reduce distribution costs, and limit monopolistic structures. Individuals can easily access health services and attend educational activities through transportation activities (Erdogan, 2020a, 2020b). However, access to transportation is not without cost. The Intergovernmental Panel on Climate Change (2014) (IPCC) reported that transportation and its sub-sectors accounted for approximately 14% of total anthropogenic emissions. Muñoz-Villamizar et al. (2020) argued that an increase in urban population would inevitably lead to an increase in transportation demand. The International Energy Agency (2020) reported that environmental pollution might increase due to increasing transportation demands. In this regard, reducing transport-led environmental pollution is one of the significant targets of international treaties. For instance, the Kyoto Treaty highlighted transport-originated pollution as one of the important environmental burdens for countries (Chapman, 2007). Besides, great significance has been attributed to meeting the demand for accessible, safe, affordable, and sustainable transportation in the sustainable development goals (SDGs). Transportation activities would be expected to be the primary driving force behind a growing energy demand, particularly in developed countries, which spur environmental degradation (Erdogan, 2020a, 2020b; Georgatzi et al., 2020; United Nations, 2020). Thus, efficient transport demand management will help achieve climate action (SDG-13) and sustainable transport (SDG-11.2). Based on this theoretical framework, we employed the following model to investigate the nexus between transport demand and environment nexus in G-7 countries for the period spanning 1995 to 2015:

$$\ln EF_{it} = \beta_{0i} + \beta_1 \ln Y_{it} + \beta_2 \ln Y_{it}^2 + \beta_3 \ln AR_{it} + \beta_4 \ln RL_{it} + \beta_6 \ln D_{it} + \beta_6 \ln F_{it} + \beta_7 \ln R_{it} + \varepsilon_{it} \tag{1}$$

where EF represents ecological footprint per capita, Y is the gross domestic product (GDP) per capita (constant, 2010 US$), and Y_{it}^2 is GDP per capita square. The AR is airline transport demand (number of passengers (carried)), RL is the railway transport demand (number of passengers (carried)). AR and RL were employed as proxies for air and railway transport demand. D is the democracy index, F is the fossil fuel energy consumption (% of the total), and R is renewable energy consumption (% of total final energy consumption). Data for ecological footprint were obtained from the Global Footprint Network (2019), whereas data for GDP per capita (Y), fossil fuel energy consumption (F), and renewable energy consumption (R) were retrieved from World Development Indicators published by the World Bank (2020). We constructed a democracy dataset (i.e., a composite index) by employing two different sub-components of law-order and democratic accountability estimated by taking the simple average of two indicators as an indicator of democracy. The law-order and democratic accountability indexes vary between 0 and 6, where 0 shows poor performance, while 6 shows high performance on democracy. The law-order and democratic accountability indexes were retrieved from the International Country Risk Guide (ICRG) (2020). All variables were converted to logarithmic values by taking natural logarithm, and empirical estimations were conducted using EViews 10, Stata 15 and Gauss 17.

According to Baltagi et al. (2005), panel econometrics techniques present robust and superior estimates, specifically coefficients. This is achieved by the increased power of unit root tests and cointegration analysis, given that the panel model aggregates cross-sectional and time-series data dimensions, making it comparable across countries and useful for between-countries analysis. This study leverages on the state-of-the-art and robust estimators, including second-generational panel estimation techniques like CIPS unit root, heterogeneous dynamics of long-run regression with bootstrap-corrected fixed effects alongside FMOLS for robustness. These methods circumvent issues with cross-sectional dependencies, viz. country-specific common shocks and heterogeneity that usually limit panel data models. Thus, our methods employed to explore the nexus between sampled variables provide robust estimates and unbiased inferences for policy formulation.

Contrary to the static model presented in Eq. (1), we re-estimated the proposed model using a dynamic panel technique that controls for heterogeneous effects and omitted-variable bias. Hence, it produces consistent and robust parameters. Following the empirical procedure presented in Sarkodie and Owusu (2020); Owusu and Sarkodie (2020), we adopt a dynamic panel with bootstrap-corrected fixed effects expressed as:

$$\begin{aligned}\ln EF_{i,t} = {} & \lambda \cdot \ln EF_{i,t-1} + \beta_1 \cdot \ln Y_{i,t} + \beta_2 \cdot \ln Y^2_{i,t} + \beta_3 \cdot \ln AR_{i,t} \\ & + \beta_4 \cdot \ln RL_{i,t} + \beta_5 \cdot \ln D_{i,t} + \beta_6 \cdot \ln F_{i,t} + \beta_7 \cdot \ln R_{i,t} + \delta_{i,t} + \varepsilon_{i,t}\end{aligned} \tag{2}$$

where $\ln EF_{i,t}$ is the target variable, $\ln EF_{i,t-1}$ is the lagged-dependent variable with an autoregressive coefficient $\lambda < 1$—signifying a dynamically stable relationship between ecological footprint and regressors [$\ln Y_{i,t}$, $\ln Y^2_{i,t}$, $\ln AR_{i,t}$, $\ln RL_{i,t}$, $\ln D_{i,t}$, $\ln F_{i,t}$, and $\ln R_{i,t}$], β_1, …, β_7 denote the estimated parameters performed with parametric bootstrap technique, $\delta_{i,t}$ denotes unobserved heterogeneous effects across countries while accounting for country-specific fixed effects, and $\varepsilon_{i,t}$ is the error term across cross-sections i=1, …, N and period t =2, …, T. The model specification in Eq. (2) is estimated using both cross-sectional heteroskedasticity and contemporaneous cross-sectional dependence for resampling of the error term—with either burn-in or heterogeneous analytical initializations. Both standard errors and confidence intervals are estimated using the fixed-effects bootstrap distribution estimator (De Vos et al., 2015).

We implemented a cross-section dependence (CD) test developed by Pesaran (2004) to investigate cross-section dependence among variables and models. We unearthed the stationarity properties of sampled variables—which is cross-sectionally independent—by using Im–Pesaran–Shin (IPS) unit root test proposed by Im et al. (2003) to investigate the unit root properties. The IPS estimation can be carried out by using Eq. (3):

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t} + \varepsilon_{it} \tag{3}$$

where α_i and β_i extended as $\left(1-\phi_i\right)\mu_i$ and $-1(1-\phi_i)$, respectively. $\Delta y_{it} = y_{it} = y_{it} - y_{i,t-1}$. The IPS test adopts "non-stationarity" in the null against "stationarity" in the alternative. Moreover, we utilized the cross-sectionally augmented IPS (CIPS) test proposed by Pesaran (2007) to investigate the stationarity of cross-sectionally dependent variables. One can implement the CIPS test by taking simple averages of country-specific estimations: $CIPS = \sum_{i=1}^{N} CADF_i/N$. The CIPS method adopts "non-stationarity" in the null against "stationarity" in the alternative. Due to non-normal distributions, critical values of the CIPS test for different sample sizes are estimated by Monte Carlo methods.

After determining the integration level of the variables, we conducted Pedroni (1999) method to examine the existence of possible cointegration in the model. The Pedroni cointegration form of Eq. (1) can be estimated by using the following specification:

$$\varepsilon_{it} = \psi_i \varepsilon_{it-1} + \sum_{k=1}^{K_i} \psi_{ik} \varepsilon_{it-k} + v_{it} \tag{4}$$

Pedroni's (1999) test adopts "no-cointegration" in the null against "cointegration" in the alternative. To estimate long-run coefficients, we used the fully modified ordinary least squares (FMOLS) approach developed by Pedroni (2000). The panel specification of the FMOLS method can be applied as (Erdogan, 2020):

$$\beta_{GFMOLS} = N^{-1} \sum_{i=1}^{N} \beta_{FMOLSi} \tag{5}$$

where β_{FMOLSi} is computed by employing country-specific FMOLS computation of Eq. (1). The t-statistics for the coefficients can be calculated as: $t_{\beta_{GFMOLS}} = N^{-1/2} \sum_{i=1}^{N} t_{\beta_{FMOLSi}}$.

3.2 Empirical results

We began our analysis by implementing a CD test to examine the effect of common global shocks—in this way, the potentiality of biased estimation is hindered, producing robust parameters for policy proposals. The CD test results (Table 2) show the null hypothesis of "no cross-section dependence" is accepted in railway transport demand, whereas the null hypothesis of cross-section dependence is accepted for other variables. Hence, traditional panel unit root techniques can be implemented for railway transport demand, whereas panel unit root tests that perform well under cross-section dependence are feasible for the remaining variables. Moreover, the null hypothesis of "no cross-section dependence" is accepted for the cointegration model. Thus, one can implement first-generation panel cointegration tests and parameter estimation (Erdogan et al., 2020b).

We used the IPS test as a first-generation unit root method to determine stationarity levels of railway transport demand. The findings (Table 3) show that the null hypothesis of "unit root" is accepted at a 5% significance level for railway transport demand in level. In contrast, it turns stationary at a 5% significance level in the first difference.

After determining the integration levels of the cross-sectionally independent variable, we implemented the CIPS test to investigate the integration level of the cross-sectionally dependent variables. The CIPS results in Table 4 reveal that ecological footprint, income, income square, airway transport demand, democracy, fossil energy, and renewable energy consumption follow the unit root process at 5% significance levels in level. However, the first difference of such variables follows the stationary process at a 5% significance level.

Table 2 CD test results

Test	MODEL	*EF*	*Y*	Y^2	AR	RL	D	F	R
CD -Stat	1.350 (0.176)	13.610 (0.000)	16.200 (0.000)	16.190 (0.000)	12.370 (0.000)	1.330 (0.180)	4.54 (0.000)	5.380 (0.000)	15.960 (0.000)

EF represents ecological footprint per capita, *Y* is the gross domestic product (GDP) per capita (constant, 2010 US$), Y^2 is GDP per capita square, *AR* is The *AR* is airline transport demand (number of passengers (carried)), *RL* is the railway transport demand (number of passengers (carried), *D* is the democracy index, *F* is the fossil fuel energy consumption (% of the total), and *R* is renewable energy consumption (% of total final energy consumption))

Table 3 IPS Results

	Model 1	Model 2
	c + t	c + t
Indicator	$\bar{t}$	$\bar{t}$
RL	− 1.326 (0.923)	− 3.722 (0.000)

Maximum lag length was used as $k = 2$. Probability values of the IPS test were reported in parenthesis. Model 1: Level, Model 2: 1st Difference, c: constant, t: trend

Table 4 CIPS results

	Model 1	Model 2
	c + t	c + t
Indicator	$\bar{t}$	$\bar{t}$
EF	− 2.883	− 4.256
Y	− 1.303	− 3.157
Y^2	− 1.906	− 3.153
AR	− 2.332	− 4.896
D	− 2.617	− 4.096
F	− 1.477	− 5.043
R	− 2.344	− 5.327

Maximum lag length was used as $k = 2$. Model 1: Level, Model 2: 1st Difference, c: constant, t: trend. Critical values for CIPS method are − 2.76 (10%), − 2.94 (5%), and − 3.30 (1%), respectively

EF represents ecological footprint per capita, *Y* is the gross domestic product (GDP) per capita (constant, 2010 US$), Y^2 is GDP per capita square, *AR* is airline transport demand (number of passengers (carried)), *RL* is the railway transport demand (number of passengers (carried), *D* is the democracy index, *F* is the fossil fuel energy consumption (% of the total), and *R* is renewable energy consumption (% of total final energy consumption))

Table 5 Pedroni (1999) test results

	Stat.
Modified PP	2.830 (0.002)
PP	− 5.364 (0.000)
ADF	− 5.024 (0.000)

Probability values for the Pedroni cointegration test are provided in the parenthesis. PP: Phillips–Perron, ADF: augmented Dickey–Fuller

The possibility of the emergence of cointegration nexus among variables occurs in the case of integrational levels at *I (1)*. Therefore, we implemented the Pedroni approach to investigate whether the variables are cointegrated in the long run. The Pedroni test findings (Table 5) confirm the rejection of the null hypothesis of "no cointegration" at a 5% significance level in three different statistics—therefore, income, the second-degree polynomial of income, air and railway transport demand, democracy, fossil, and

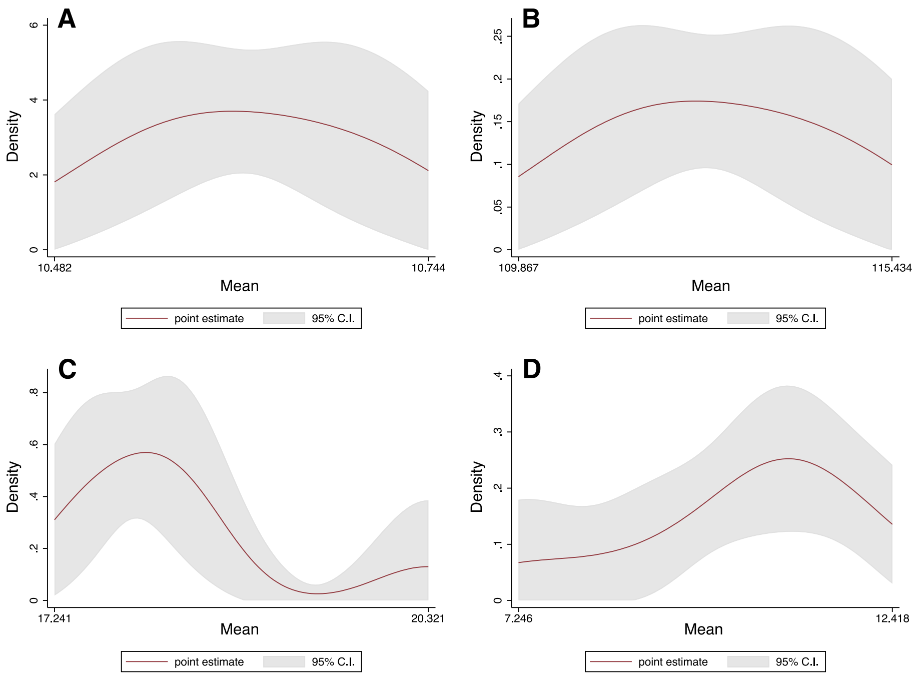

Fig. 2 Panel kernel-based heterogeneous effects: **A** GDP, **B** GDP^2, **C** airline transport demand, **D** railway transport demand

renewable energy have a long-run effect on ecological footprint. Next, we assessed heterogeneous effects across countries using the novel panel kernel-based heterogeneous test with output plots presented in Figs. 2 and 3. Evidence from Figs. 2 and 3 reveals the mean point estimates of data series are within the 95% confidence interval, thus confirming heterogeneous effects across countries.

The long-run coefficient estimation results using FMOLS specification are shown in Table 6. Accordingly, income positively affects ecological footprint (i.e., at p value < 0.05), whereas income square negatively affects ecological footprint (i.e., at p value < 0.05). These results validate the existence of the EKC hypothesis. The empirical results infer poor environmental quality at the initial economic pathway in G-7 countries. However, ecological quality improved after passing a certain income level, viz. the turning point of the inverted U-shaped curve. In other words, environmental degradation tends to increase in the first phase of the EKC, while degradation declines in the second stage of the EKC. These findings confirm one part of existing literature (see Erdogan et al. (2020a); Acaravci and Akalin (2017); Sarkodie and Adams (2018), while in contradiction with another set of existing literature (see Aslan et al. (2018); Ozcan et al. (2018) Sarkodie and Strezov (2019)). Moreover, we computed a turning point of income as US$ 45,738 per capita. In this regard, Canada, Japan, and the USA have already passed the threshold level of income, whereas France, Germany, Italy, and UK are yet to achieve such a target (i.e., level of revenue in 2015).

Moreover, a 1% increase in air transport demand increases ecological footprint by 0.12% (i.e., at p value < 0.05); hence, air transport demand positively affects

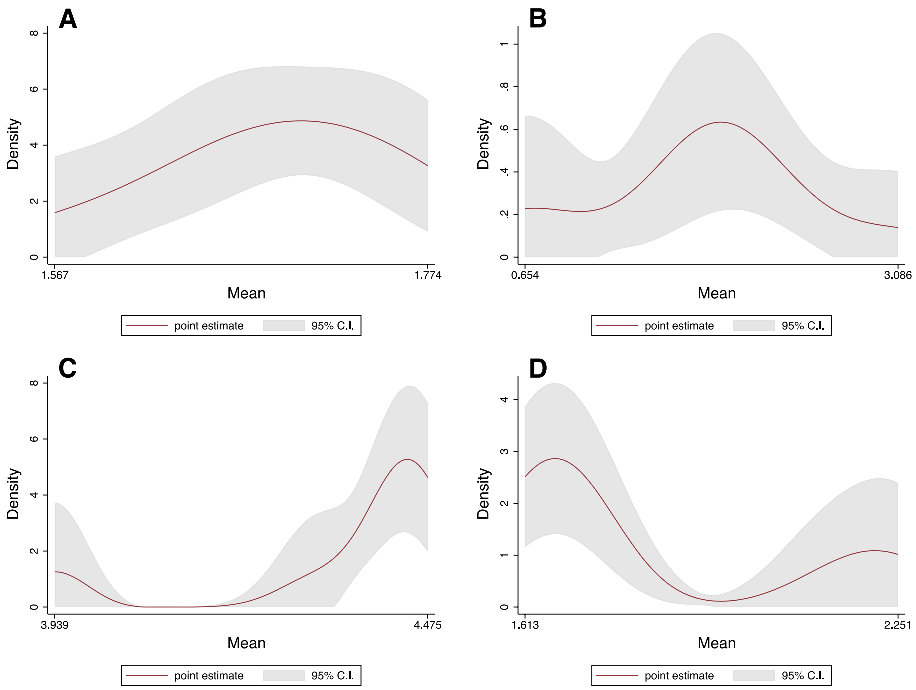

Fig. 3 Panel kernel-based heterogeneous effects: **A** democracy index, **B** renewable energy consumption, **C** fossil fuel energy consumption, **D** ecological footprint per capita

environmental degradation. This implies a positive shock in travel demands by air transportation may lead to a rise in environmental pollution levels. These findings confirm the results of Erdogan (2020); Erdogan et al. (2020a) while contradicting Pereira and Pereira (2017). The railway transport demand has a negative but statistically insignificant effect (i.e., at p value > 0.05) on ecological footprint. Thus, we confirm no statistically significant nexus between railway transport demand and ecological footprint. This is consistent with Georgatzi et al. (2020); Neves et al. (2017), while in contrast to Erdogan (2020); Erdogan et al. (2020a), Pereira and Pereira (2017). Besides, 1% increase in democracy escalates ecological footprint by 0.18% (i.e., at p value < 0.05). Democracy has a positive and statistically significant effect on ecological footprint—implying democratization exacerbates the environmental condition in G-7 countries. This supports the findings of Akalin and Erdogan (2021); Mak Arvin and Lew (2011); Charfeddine and Mrabet (2017), while in contrast to Bernauer and Koubi (2009); Pellegrini and Gerlagh (2006); Adams and Klobodu (2017). Fossil energy use has a positive and statistically significant effect on ecological footprint—consequently, a 1% increase in fossil fuel consumption increases ecological footprint by 0.33% (i.e., at p value < 0.05). In contrast, a 1% increase in renewable energy utilization decreases ecological footprint by 0.17% (i.e., at p value < 0.05), inferring the adoption of renewables safeguards ecological deterioration. The findings related to fossil fuels and renewables are consistent with several existing studies. The larger coefficient of fossil fuels shows the mitigating effect of renewables is yet to offset the deteriorating effect of fossil fuel energy consumption. This segment of empirical results is parallel with theoretical

Table 6 FMOLS estimation results

Indicators	Coefficients	*t*-stat	Prob.
Y	46.535	1250.074	0.000
Y^2	−2.168	−39.631	0.000
AR	0.121	2.054	0.042
RL	−0.003	−0.061	0.950
D	0.182	5.095	0.000
F	0.332	13.301	0.000
R	−0.178	−4.756	0.000

The covariance for the long run was computed by using the Newey–West fixed bandwidth and Bartlett kernel based on the heterogeneity of long-run variance

EF represents ecological footprint per capita, Y is the gross domestic product (GDP) per capita (constant, 2010 US$), Y^2 is GDP per capita square, AR is airline transport demand (number of passengers (carried)), RL is the railway transport demand (number of passengers (carried), D is the democracy index, F is the fossil fuel energy consumption (% of the total), and R is renewable energy consumption (% of total final energy consumption))

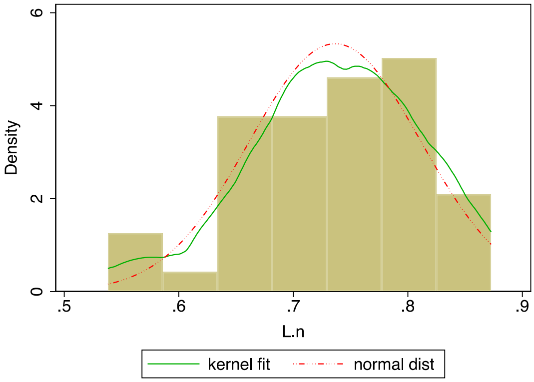

Fig. 4 Bootstrap distribution dynamics of GDP, GDP^2, airline transport demand, railway transport demand, democracy index, renewable energy consumption, and fossil fuel energy consumption in ecological footprint function

expectations and former literature (see Lv (2017); Farzanegan and Markwardt (2018); Kim et al. (2019)).

We further validate the FMOLS estimator using a panel dynamic bootstrapped-corrected estimator with country-specific fixed effects. To further verify the estimated dynamic model, we followed the testing procedure expounded in Owusu and Sarkodie (2020) to examine the distributional structure of the estimated residuals (Fig. 4). We employed the bootstrap distribution for diagnostic analysis—displayed in histogram alongside kernel fit and normal distribution plots depicted in Fig. 4. The bootstrap distribution dynamics of the estimated residuals—designated by the histogram plot presented in Fig. 4—show a kernel fit that follows the normal distribution. The bootstrap distribution of the sum of autoregressive parameters reveals a seemingly perfect prediction of the estimated model that validates the robustness of the model specification and statistical inferences. Thus, confirming the residual independence of the estimated dynamic model achieves convergence and stability over time and across sampled countries.

Table 7 Heterogeneous dynamics of ecological footprint with bootstrap-corrected fixed effects

	Coefs	t	$P>t$	[95% Conf. Interval]	
EF_{t-1}	0.752*** (0.075)	10.050	0.000	0.604	0.900
Y	14.998*** (5.603)	2.680	0.008	3.910	26.086
Y^2	−0.712*** (0.263)	−2.710	0.008	−1.233	−0.191
AR	0.043 (0.027)	1.600	0.113	−0.010	0.097
RL	−0.006 (0.011)	−0.560	0.573	−0.029	0.016
D	0.015 (0.057)	0.270	0.790	−0.097	0.128
R	−0.044*** (0.014)	−3.230	0.002	−0.071	−0.017
F	0.160** (0.066)	2.410	0.017	0.029	0.292

(..) denotes the bootstrapped standard errors, ***, and ** represent statistical significance at $p<0.01$ and $p<0.05$. Confidence interval [95% Conf. Interval] for the t-distribution calculated with bootstrapped standard errors, whereas statistical inferences are performed with parametric bootstrap technique

EF represents ecological footprint per capita, *Y* is the gross domestic product (GDP) per capita (constant, 2010 US$), Y^2 is GDP per capita square, *AR* is airline transport demand (number of passengers (carried)), *RL* is the railway transport demand (number of passengers (carried), *D* is the democracy index, *F* is the fossil fuel energy consumption (% of the total), and *R* is renewable energy consumption (% of total final energy consumption))

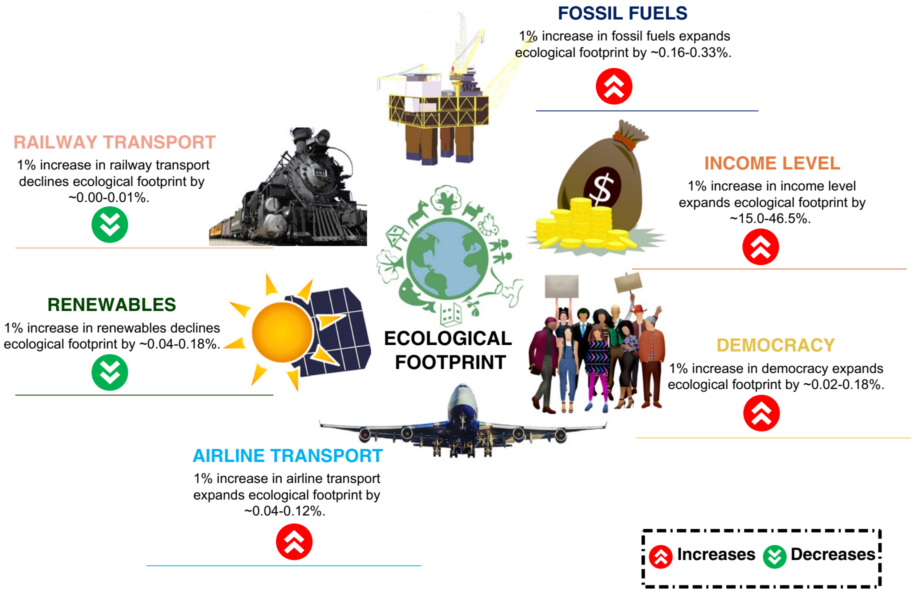

Fig. 5 Summary of estimated findings from both FMOLS estimator and panel bootstrap-corrected fixed-effect analysis

The results of the estimated model are presented in Table 7, whereas the summary of estimated findings from both the FMOLS estimator and panel bootstrap-corrected fixed-effect analysis is depicted in Fig. 5. Similar signs of FMOLS coefficients are observed in the heterogeneous panel estimation results. However, the level of statistical significance differs because of the lagged-dependent ecological footprint that dynamically makes it possible to achieve statistical convergence. The lagged-dependent ecological footprint (EF_{t-1}) with a statistically significant positive autoregressive coefficient of 0.752 is less than 1—implying a dynamically stable relationship between ecological footprint, income, squared of income, airline transport demand, rail transport demand, democracy, renewables, and fossil fuels. This infers that historical trends of ecological footprint predict 75% of future changes in environmental status based on the *ceteris paribus* assumption. Thus, ecological destructive levels or patterns of ecological sustainability across countries are determined by historical consumption patterns of ecological resources. Consistent with the FMOLS estimator, an inversed U-shaped relationship between ecological footprint and income level is observed. While a 1% increase in income level expands ecological footprint by 15%, the squared component of income level declines ecological footprint by 0.71%. Increasing the share of fossil fuels in total energy consumption escalates ecological footprint by 0.16%. However, diversification of the total energy consumption with a 1% share of renewables declines ecological footprint by 0.04%.

4 Discussion

This study executed the test of environmental sustainability among air travel demand, rail transportation demand, demographic policies, and energy consumption from conventional energy sources and renewable energy in G7. The nexus between these indicators has far-reaching implications for environmental sustainability targets in G7 economies. For instance, the significant positive interaction between income level and ecological degradation is suggestive that at higher economic growth, there is a compromise for environmental quality—as such, validating the EKC phenomenon. Thus, this study gives credence to the scale effect phase of development in G7 over the investigated period, where the emphasis is on economic growth relative to environmental status. This outcome is in line with Balsalobre–Lorente's et al. (2018) for 5-EU countries. In the case of G7 policymakers and energy specialists to pursue green-development strategies, an economy that thrives on clean and sustainable energy that is conscious of the threshold of where trade-off exists between economic growth becomes environmentally friendly (Bekun et al., 2019). To maintain the momentum of environmental sustainability in the transportation sector, especially those that stern from air and rail transport demand is affected by demographic policies amidst global energy demand. There is a need for a sustainable transition to full-fledged alternative and clean energy sources (renewables, nuclear) and innovation in the transportation sector and economic structure. For instance, there is the need for government officials and private investors in the aviation sector to embrace low-carbon efficient planes that are in line with global renewable expectations for a pristine ecosystem—as already witnessed in some quarters of the world (Erdogan et al., 2020a). The need for more strides in renewable energy in G7 is evidence of the positive relationship between fossil-fuel energy sources that deteriorate environmental quality. As such, government administrators can pursue ecological sustainability by adopting the polluter-pays principle—a phenomenon that emphasizes the need for regulation(s) on the violator of environmental rules subject to cost damage. We further observe that government policies affect environmental quality, as democratic-based policies exacerbate ecological quality. To achieve the environmental sustainability target, there is a need for a revamp of government regulation(s), as it concerns demographic indices. Additionally, rail transport demand shows a desirable relationship with environmental quality. To maintain the positive strides of renewable energy, it calls for responsible energy consumption in G7 by diversifying the energy mix (SDG-11 and 12), which by extension aids in climate change mitigation (SDG-13).

5 Conclusion

By using annual frequency data for G7 economies, this study explored the connection between air travel demand, rail transportation demand, institutional policies, and energy consumption from conventional energy sources and renewable energy on environmental degradation measured by a broader proxy, viz. ecological footprint. For sound and efficient analysis, panel techniques that account for cross-sectional dependence and heterogeneity were employed. A long-run equilibrium relationship was confirmed over the sampled period. The empirical results validated the existence of the EKC concept in G7, where a trade-off exists between GDP growth and environmental quality. Our empirical results outline policy implications for stakeholders—where there is the need for caution on green development for ecological sustainability without compromising sustained economic development.

Additionally, we found that fossil-fuel sources hamper environmental quality, thus suggesting the need for more innovative and clean energy sources like renewables (i.e., bioenergy, wind, photovoltaic, hydro, solar, and thermal energy sources). There is also a need for drafting policies that engender environmental sustainability in lieu of the democratic dynamics of G7 architecture. The revelation of air transport-induced environmental pollution is indicative to aviation agents for alternative innovation to conduct operations while reducing environmental degradation. This can be achieved by the adoption of planes with energy-efficient, low-carbon emission, and clean technologies that is more committed to environmental treaties and actions. On the contrary, rail transport and renewable energy improve environmental quality, and this momentum should be sustained for ecological sustainability, which is of utmost desire. Conclusively, this study explored the nexus between air travel demand, rail transportation demand, democracy, income level, and energy consumption from fossil fuels and renewable sources on ecological footprint. However, subsequent studies could explore the theme and account for asymmetry while considering other developed blocs. There is also limited documentation on disaggregated data modeling, which could be explored by future studies on the extension of the EKC to the transportation sector-induced pollution.

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Author contributions SE did formal analysis, writing—original draft, and writing—review and editing; SAS done formal analysis, visualization, supervision, writing—original draft, writing—original draft, writing—review and editing. FFA was involved in writing—original draft, writing—review and editing. FVB contributed to conceptualization, writing—original draft, writing—review and editing; PAO provided formal analysis, writing—original draft, writing—review and editing.

Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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