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Do green technology innovation, environmental policy, and the transition to renewable energy matter in times of ecological crises? A step towards ecological sustainability

Aamir Javed [c,*], Agnese Rapposelli [c], Feroz Khan [a], Asif Javed [b], Nabila Abid [d]

[a] *Department of Management and Business Administration, "G.d' Annunzio" University of Chieti-Pescara, Italy*
[b] *Department of Advanced Technologies in Medicine and Dentistry, "G.d' Annunzio" University of Chieti-Pescara, Italy*
[c] *Department of Economic Studies, "G.d' Annunzio" University of Chieti-Pescara, Italy*
[d] *Department of Strategy & Entrepreneurship, EM Normandie Business School, Métis Lab, Le Havre, France*

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ABSTRACT

Over the past few decades, ecological damage has been humanity's greatest threat. It is possible that factors such as green technology innovation, environmental policy, and renewable energy consumption can play an essential role in the process of achieving ecological sustainability. Therefore, the present study aims to investigate the impact of green technology innovation, environmental policy, and renewable energy consumption, along with economic growth, trade openness, and urbanization, on ecological sustainability in the presence of the environmental Kuznets curve hypothesis for a group of G-7 economies from 1994 to 2018. For this purpose, we employed the long-run mean estimation approaches (FMOLS, DOLS, FE-OLS) along with the Panel Quantile Regression technique to produce the heterogeneous results at various levels of ecological footprint. The panel quantile regression findings report that green technology innovation, environmental policy, renewable energy consumption, and urbanization promote ecological sustainability by reducing the ecological footprint at all quantiles. However, the effect of renewable energy consumption on ecological sustainability is statistically insignificant at the 10th quantile. Further, the significant positive impact of economic growth and negative impact of economic growth square on ecological footprint confirms the environmental Kuznets curve hypothesis. Moreover, the findings indicate that trade openness stimulates the ecological footprint and, as a result, reduces ecological sustainability. Further, the findings of long-run mean estimates are similar to panel quantile regression outcomes. The findings of the present study suggest that the G-7 countries need well-designed strict policies that emphasize and help these countries increase the share of renewable energy consumption compared to non-renewable and promote green technological innovation in G-7 through financial aid, and stringent environmental policy instruments (e.g., taxes) that help these countries ensure the ecological sustainability.

1. Introduction

The unsustainable production and consumption activities worldwide are the root cause of the triple planetary threats, i.e., climate change, biodiversity loss, and pollution. To address these concerns, the United Nations has promulgated Sustainable Development Goals (SDGs) to ensure growth based on the triple bottom line framework, i.e., social, environmental, and economic aspects. As a result, this has made the sustainable development paradigm of prime eminence for governments and policymakers. In this regard, the developed nations have a very important role to play, especially because they contribute the most to the world's economic prosperity and more so because they work as a torch bearer for the rest of the economies to follow in terms of policy formulation and implementation. However, it is pertinent to consider an indicator responsible for environmental degradation to identify and address the issue at the core. The most comprehensive indicator that corresponds to a wider range of environmental sustainability is ecological footprint (EFP). In this regard, most of the studies in the literature only take carbon emissions (CO_2) as an indicator to capture environmental degradation, which is not justifiable because other

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* Corresponding author.

E-mail addresses: aamir.javed@unich.it (A. Javed), agnese.rapposelli@unich.it (A. Rapposelli), feroz.khan@unich.it (F. Khan), asif.javed@unich.it (A. Javed), nabilaabid032@gmail.com (N. Abid).

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components such as build-up land, cropland, fishing grounds, forest products, and grazing land end up being neglected (Dembińska et al., 2022; Wang et al., 2023). In this case, the EFP, which encompasses the aforementioned components, is regarded as a more effective indicator to gauge environmental degradation in any country.

The status of the EFP can be gauged through the ecological accounting framework, which indicates that if the demand of humans for natural resources exceeds the available resource production and waste absorption capacities (i.e., biocapacity), it leads to ecological imbalance or ecological deficit. If the aforementioned definition is flipped, it corresponds to the term ecological surplus (Global Footprint Network, 2023). Several parameters drive the EFP. On a broader scale, these parameters can be affected by domestic and international economic activities (Khan et al., 2022). Developed nations such as the G-7 countries have shown substantial economic growth in this regard. Around 30.7 % of the world's economy is contributed by the G-7 countries (Statista, 2023). For benchmark purposes, the carbon emissions from G-7 countries contributed 28 % of global emissions in 2019 (BP, 2021). To assess the status of environmental degradation in G-7 countries, this study considers the timeline of 1994 to 2018 because of data constraints. To gauge the contribution of EFP by these countries, a comparison is drawn between 1994 and 2018 using the global footprint network database. As evident from Fig. 1 below, all the countries in G-7 are facing an ecological deficit except for Canada in 1994 and 2018. Another interesting thing to notice in Fig. 1 is that though the EFP in both years has decreased, so has the biocapacity. Cumulatively, the G-7 countries are subjected to ecological deficits in both years. This means that these countries do not have adequate levels of ecological assets to meet the demands of their population more sustainably.

To study the variation in EFP, it is important to identify and discuss the relevant parameters driving ecological degradation in the G-7 countries. An understanding of these parameters will ensure effective policy formulation. For this purpose, a total of seven distinctive parameters, including green technology innovation (GTI), environmental policy (EP), renewable energy consumption (REN), economic growth (GDP), square of economic growth (GDP^2), trade openness (TO), and urbanization (URB) are being proposed to study the variation in the EFP in G-7 countries. An explanation of each variable and its importance and relation to ecological footprint is outlined.

The rationale for determining parameters for gauging EFP has to be based on the dynamics of the G-7 economies. The G-7 nations are characterized by higher levels of urbanization, attributing 75.59 % as opposed to the average urbanization level of the world, which is 54 %. In this case, Japan is considered the most urbanized nation, with urbanization levels of 93 %. Meanwhile, the least urbanized nation, Italy, still has 69 % levels of urbanization (Ahmed et al., 2020). The urban population in these countries is considered to have a decent purchasing power which gives them the privilege to engage in sustainable activities such as the consumption of cleaner energy technologies and producing lesser waste (Danish and wang, 2019). However, economic growth also

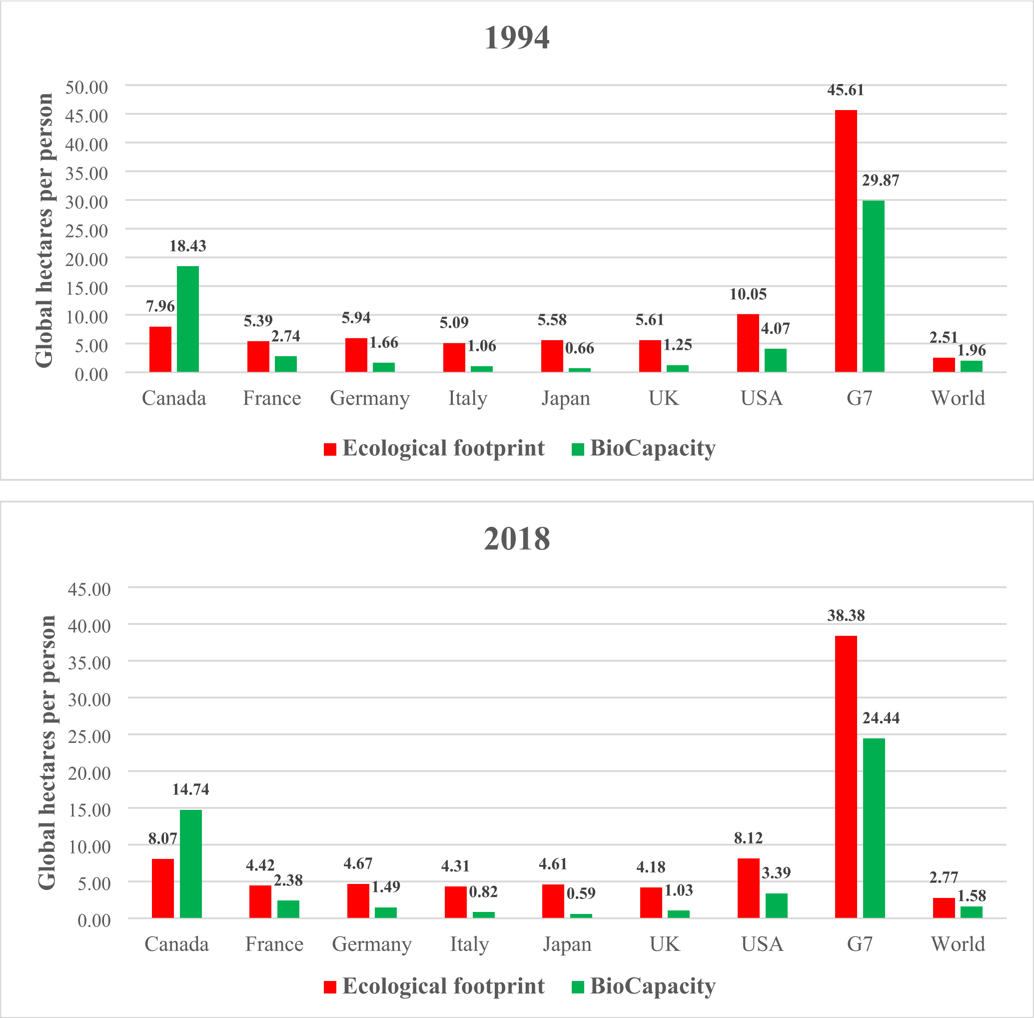

Fig. 1. Ecological footprint vs biocapacity in G-7 countries.
(Source: Global Footprint Network, 2023)

means an increase in the extraction of natural resources, which in turn fosters enhanced deforestation, agriculture, and mining (Danish et al., 2019). These activities foster economic growth but, on the other hand, decrease biocapacity and enhance the EFP. An increase in urbanization also means increased transportation activities and enhanced utilization of non-renewable energy technologies on the state level.

Additionally, to prevent environmental degradation and achieve the SDGs set forth by the United Nations, nations worldwide have adopted a wide range of pro-environmental measures over the past few years. Funding research and development activities is one of the most important steps many take (Jiang et al., 2023). Numerous governments, organizations, and businesses have started investing more money in R&D. Developed nations such as the G-7 have the capacity and capability to invest in R&D activities that foster green technological innovation. Global spending in R & D has increased dramatically to an all-time high of USD 1.7 trillion (UIS, 2022). The G-7 countries account for a disproportionately large fraction of this total. Fig. 2 visually represents the R&D spending (%GDP) for the G-7 nations. In terms of domestic spending on R&D in G-7 countries as of the year 2021, the USA has made the largest investment among the G-7 nations (3.46 % of GDP), followed by Japan (3.30 % of GDP), the UK (2.91 % of GDP), France (2.22 % of GDP), Canada (1.70 % of GDP), and Italy (1.45 % of GDP) (OECD, 2022).

Further, with tight laws and policies in place, these countries are willing to invest in energy-efficient manufacturing technologies with less emissions and waste production. Also, abiding by the circular economy principles, the industries in such countries aim to minimize their waste in their upstream and downstream supply chains. Implementing lean manufacturing practices and having a strong symbiotic network and reverse logistic infrastructure means less waste generation. All these measures lie under green technology innovation, aiming to hinder environmental degradation, preserve natural resources, and engage in advanced manufacturing and recycling processes (Sharif et al., 2022). The results of such measures, i.e., the adoption of sustainable technologies accompanied by clean energy production and consumption activities, have the potential to acquire 90 % of the environmental degradation reduction goals in the world (Afshan et al., 2022). However, in this regard, the role of environmental regulations is considered to be very essential, which can be made possible through stringent environmental policies. However, the problem with the G-7 countries is the lack of synergies of action with such diverse policy formulation and implementation in place (Sarfraz et al., 2023). An example of such policies can be the infliction of the carbon tax on unsustainable production and transportation activities. Other policies include the production and consumption of cleaner energy technologies. In this case, the role of renewable energy technologies such as wind, solar, biomass, hydro, and geothermal is getting considerable attention. The adoption of renewable energy in the G-7 is considered to address the problems of environmental degradation as well as ensure energy security.

Further, the group of G-7 nations has pledged to increase the share of renewable energy in total energy production to 60 % by 2030. Fig. 3 depicts a similar upward trajectory in the use of renewable energy across the G-7 nations. The figure illustrates that in 2018, Canada utilized 22 %, Italy 17.08 %, Germany 16.12 %, France 15.21 %, the UK 13 %, the USA 10.12 %, and Japan 7.22 % of clean energy as a percentage of total final energy consumption, respectively. Our research shows that among the countries represented in our sample panel, Canada and Italy consume a sizeable portion of clean energy in their total final energy mix. Therefore, the particular variable is considered to be of prime importance in gauging the EFP of such nations (Usman et al., 2021).

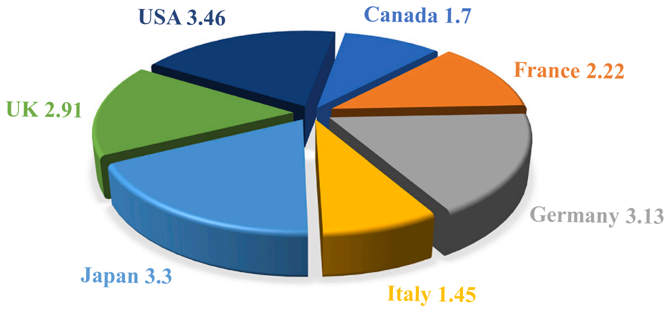

Fig. 2. G-7 nations R&D expenditure (% of GDP).
(Source: OECD)

Further, trade openness is another variable considered an important factor in the sustainable GDP growth of the G-7 countries. In this regard, an optimal level of imports and exports plays a crucial role. The overall imports and exports of the G-7 in 2019 were 35 % and 32 %, respectively. Among these nations, the United States has the most imports and exports on a global level (Wang et al., 2022). It is important to understand that TO may positively or negatively impact any nation's ecological footprint. However, considering the level of maturity in the industrialization of the G-7, these countries are in the phase where they are investing and providing opportunities in environmentally friendly technologies. It is known that economic growth in any country is considered a proxy in gauging economic growth. The same variable has also been assessed in gauging environmental degradation. However, gauging environmental degradation solely in the variation of GDP is considered to yield inconclusive results (Ozturk et al., 2016). For instance, a rise in GDP reflects rapid economic growth, whereas if the square of the same variable is taken, it yields a non-linear relationship between economic growth and environmental degradation, giving rise to the term Environmental Kuznets Curve (EKC) hypothesis. The EKC hypothesis yields an inverted U-shape relationship between economic growth and environmental degradation (see Fig. 4). It can be explained that there is less awareness and preference for safeguarding the environment in the initial phases of economic growth. However, when certain economic growth targets are achieved, there is an increasing interest in preserving the environment (Kostakis and Arauzo-Carod, 2023). The importance of this variable makes it pertinent to engage it in gauging the EFP in the G-7 countries, as the literature suggests mixed results regarding the relationship between the two in other contexts (Sabir and Gorus, 2019).

The importance of the G-7 economies in economic development and their interest in attaining the SDGs makes it pertinent for the researchers to gauge the environmental quality of such countries and provide relevant policy recommendations. The issue with the G-7 economies is their dependability on high levels of production and consumption activities, which, as a result, is triggering the EFP, consequently bringing it under the radar for causing environmental degradation (Khan et al., 2022). Fig. 1 shows that besides Canada, all the other nations in the G-7 countries are facing an ecological deficit. The cumulative results for G-7 countries showcase ecological deficit for both years. To gauge the EFP of such countries and provide necessary policy recommendations, it is pertinent to utilize advanced empirical econometric tools and consider all those crucial variables responsible for causing ecological degradation in such countries. The present research contributes to the body of literature in many ways. Firstly, the study considers a more conclusive indicator for gauging environmental degradation in the context of G-7 countries, i.e., EFP, instead of just considering carbon emissions (Wang et al., 2023a). Based on the dynamics of the G-7 economies, the study further considers comprehensive and distinctive variables considered EFP drivers. These variables include GTI, EP, REN, GDP, TO, URB, and testing the EKC hypothesis. Other studies in this regard consider limited parameters for gauging the EFP in the G-7 countries, e.g. (Usman et al., 2021; Zhang et al., 2022a; Khan et al., 2022; Huang et al., 2022; Bozkaya and Dura, 2022; Wang et al., 2022; Özpolat, 2022). Considering the aforementioned variables, the study employs intricate and advanced econometric tools and tests for analyzing data from the global footprint network database from 1994 to 2018. Instead of the commonly used traditional mean regression estimation techniques in the literature, the current research utilizes the Panel Quantile Regression (PQR) approach,

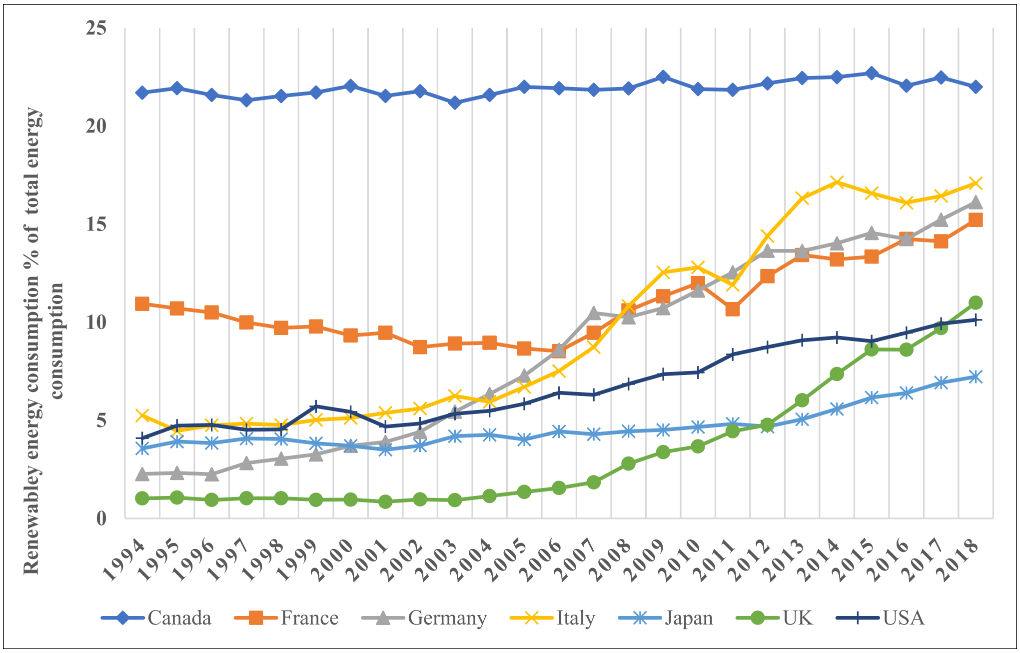

Fig. 3. Renewable energy consumption trend in G-7 nations.
(Source: WDI)

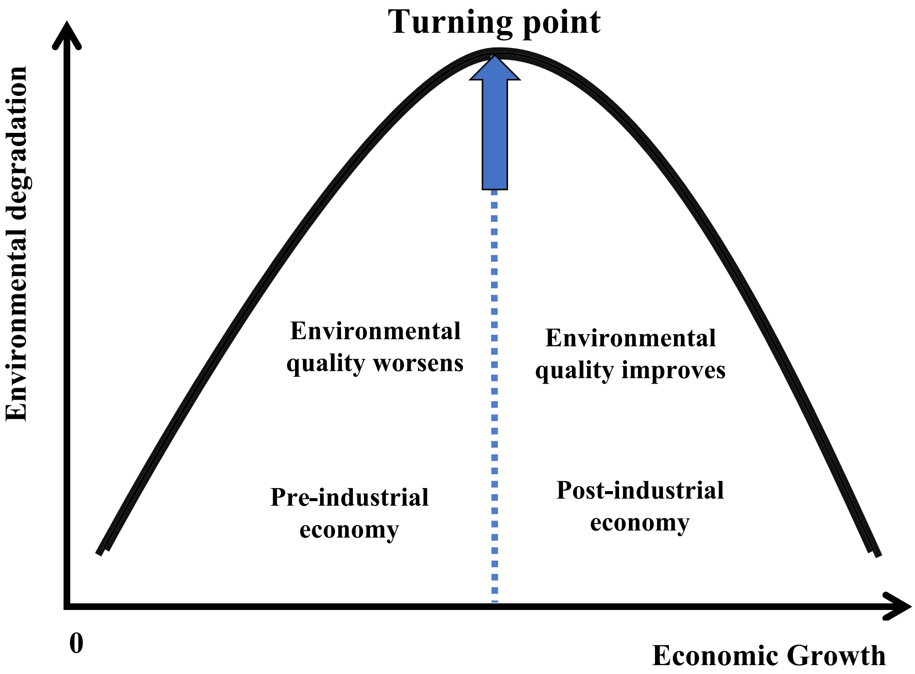

Fig. 4. Environmental Kuznets Curve (EKC).
(Source: Authors own creation)

which has the attribute of providing more elaborate results (Wang et al., 2018; Ahmad and Wu, 2022; Wang et al., 2023). Unlike other studies, the current research employs a pool of 2nd generation panel econometric methods that have the characteristics of dealing with possibly critical panel data assessment problems that include cross-sectional dependency test, slope heterogeneity test, 2nd-generation panel stationarity test such as CIPS, Westerlund co-integration test, along with the application of econometric models such as FMOLS, DOLS, FE-OLS, and panel quantile regression (PQR). Further, the above-mentioned econometric models only evaluate the long-run connection between the research variables and overlook the causal association. For this, the present study also employed Dumitrescu and Hurlin's (2012) Granger causality to examine the causality direction between the study variables.

The remaining research sections are organized as follows: Section 2 offers the pertinent literature analysis. Section 3 discusses the theoretical framework, model definition, variable construction, and estimating approaches utilized. Section 4 presents the empirical result and their discussion. Finally, Section 5 offers a summary of the research and policy recommendations.

2. Literature review

2.1. Nexus between green technology innovation and ecological sustainability

In recent years, green technology innovation has gained substantial attention as a significant means of fostering environmental sustainability. Many scholars have investigated the influence of GTI on the quality of the environment. For instance, Ahmad and Wu (2022) explored the combined effect of eco-innovation, economic globalization, and green growth on environmental sustainability for 20 selected OECD economies from 1990 to 2017. The observed outcomes uncovered that GTI brings ecological sustainability to the underlying countries. Mongo et al. (2021) observed the result of GTI, TO, and REN on CO_2 emissions in 15 European countries from 1992 to 2014. The researchers demonstrated an emission reduction impact of GTI only in the long-term. Further, by employing a model called "Stochastic Impacts by Regression on Population, Affluence, and Technology" (STIRPAT), Wang et al. (2020) researched the influence of GTI on China's 30 provinces CO_2 emissions from the period 2004–2015. The findings revealed that GTI diminishes environmental health. Using 37 OECD countries' data from 1997 to 2017, Iqbal et al. (2021) studies the role of GTI and REN in reaching their carbon neutrality goals. They documented that REN and GTI promote environmental sustainability. Razzaq et al. (2023) evaluated the result of GTI and tourism development on environmental health and economic development in the top 10 GDP nations from 1995 to 2018. The findings showed that tourism development enhances environmental deprivation while GTI reduces CO_2 emissions. Sun et al. (2022a) probed the asymmetric impact of GTI and REN on environmental degradation in China from 1990Q1–2018Q4. They employed the NARDL model, and their findings revealed that positive changes in GTI have a reduced impression on ecological degradation, whereas negative shocks in GTI boost environmental hazards. Further, Akram et al. (2023) conducted a study to evaluate the role of GTI in improving environmental quality in the BRICS countries. The study's findings support the idea that fostering GTI improves environmental sustainability in the examined countries. In addition, Wei and Lihua (2023) and Alola and Adebayo (2023) also discovered that GTI significantly reduces CO2 emissions and improves ecological quality, lending credence to the idea that eco-innovation plays a pivotal role. Contrary to this, Weina et al. (2016) learned about the connection between GTI and environmental health using data from 95 Italian provinces from 1990 to 2010. Their empirical outcomes revealed that GTI has no significant reducing impact on CO_2 emissions. Further, Yuan et al. (2022a) and Yuan et al. (2022b) also looked into the link between the development of GTI and CO_2 emissions. According to the study findings, GTI considerably reduces environmental degradation. Moreover, by utilizing the data of the top 10 highest ecological footprint countries, Saqib et al. (2024) examined the impact of GTI on ecological footprint and green growth. The study's findings emphasize the importance of GTI in promoting ecological sustainability, which leads to increased green growth. In the case of E-7 nations, Dam et al. (2024) inspected the connection between technological innovation and EFP for the sake of long-term ecological viability. The empirical outcomes of the study suggest that technological innovation reduces the level of EFP and, as a result, improves ecological sustainability.

2.2. Nexus between environmental policy and environmental sustainability

In environmental preservation and long-term sustainability, EP is a key component that reveals the global level of strict and designed rules that put an explicit and implicit cost on environmentally destructive actions (Luo and Mabrouk, 2022). The number of investigations organized to explore the impact of environmental policies (EP) on environmental health is limited, and the outcomes of these studies are conflicting. For instance, Hashmi and Alam (2019) scrutinized the impact of EP and GTI on CO_2 emissions in OECD nations. They employed the STIRPAT model by using panel data from 1998 to 2014. They revealed that an increase in environmental taxes mitigates CO_2 emissions. Further, Javed et al. (2023a) studied the influence of environmental taxes on the EFP in Italy from 1994 to 2018. Their findings revealed a beneficial impact of EP on environmental health. Similarly, Rafique et al. (2022) inspected the interlinkages between environmental taxes and environmental health for a panel of 29 OECD economies. Their data demonstrated that environmental taxes boost ecological sustainability. Dai and Du (2023), using the nonlinear MMQR method, investigated the role of EP in reducing the EFP for the BRICS-T nations. The study's estimated empirical results validate the negative interdependence between EP and EFP and demonstrate that EP successfully regulates ecological deterioration. Similarly, by employing the CS-ARDL approach, Sharif et al. (2023) ascertained the EP limiting effect on environmental degradation in Nordic nations. In line with this, Rafique et al. (2022) endorsed the outcomes for OECD. In addition, Ömer and Dündar (2021) concluded that EP intensifies environmental sustainability. Contrary to this, using data from BRICS nations from 1994 to 2015, Ulucak and Kassouri (2020) revealed a positive impact of EP on ecological degradation.

2.3. Nexus between renewable energy consumption and environmental sustainability

In the case of renewable energy utilization, numerous investigations have looked at the linkage between REN and environmental health. These studies highlighted the positive effect of REN on ecological sustainability. For example, Anwar et al. (2021) studied the connection between REN and the environmental health of ASEAN nations from 1990 to 2018. Their empirical findings exposed a positive linkage between REN and the quality of the environment. Similar outcomes were also discovered by Usman et al. (2021) for 20 Asian economies by utilizing data from 1990 to 2014. Similarly, using data from 17 OECD nations from 1977 to 2010, Bilgili et al. (2016) disclosed that REN utilization reduces environmental degradation. Likewise, Shafiei and Salim (2014) have shown an inverse relation between REN and environmental deterioration in OECD countries. Further, Ulucak and Khan (2020) explored the connection between REN and EFP by using data from 1992 to 2016 from the BRICS countries. They documented a negative effect of REN on EFP, suggesting that REN promotes ecological sustainability. Alola et al. (2019) investigated the determinants that contributed to the reduction of EFP in 16 EU member countries from 1997 to 2014. They observed that REN utilization improves environmental sustainability. Sun et al. (2022b) examined the non-linear impact of REN on environmental degradation reduction in 10 top polluted nations from 1991 to 2018. Their results illustrated that REN significantly lowers environmental degradation. Bhat (2018) also suggested a similar conclusion for BRICS countries from 1992 to 2016. Wang et al. (2024a) examined the impact of REN on the ecological sustainability of G-20 nations. The findings suggest that REN significantly lessens the negative environmental impact in countries with lower quantiles, while this effect is not as pronounced in countries with higher quantiles. In line with this, Hu et al. (2018) revealed that REN helps reduce environmental degradation in 25 developing nations. Further, Khan et al. (2020) investigated the role of REN on the environmental quality in Nordic economies from 2001 to 2018. The outcomes suggested that REN enhances environmental quality. Further, Ma et al. (2024) evaluated ecological sustainability in the least and top green economies from 1990 to 2021. They identified that REN enhances ecological sustainability by lowering the level of EFP in underlying economies. Moreover, Javed and Rapposelli (2024) suggested similar outcomes for Eastern and Western European nations, Sharif et al. (2024) for the USA, Ayhan et al. (2024) for OECD nations, and Khan et al. (2024) for South Asian nations.

2.4. Nexus between economic growth and ecological sustainability

Many researchers have looked into the income-growth nexus, in the form of the EKC hypothesis, over the past few decades using various econometric techniques and data samples for various single and panel countries. However, the conclusions of these investigations are mixed. For instance, some researchers proved the validity of the EKC hypothesis (Churchill et al., 2018; Kiliç and Balan, 2018; Sapkota and Bastola, 2017; Tjoek, 2018; Destek and Sarkodie, 2019). Contrary to this, other researchers revealed that the EKC theory does not hold (Apergis, 2016; Ozcan et al., 2018; Halliru et al., 2020). For instance, Yang et al. (2022) tested the EKC hypothesis in E7 countries and established the occurrence of the EKC theory. Further, Destek and Sarkodie (2019) reported that a U-shaped relation exists between GDP and the environment in Singapore, which approved the legality of the EKC hypothesis. Aydin et al. (2023) investigated the role of GTI and REN on the EFP in European Union nations in the context of the EKC hypothesis. The findings indicate that the EKC theory only exists in Finland. Similarly, Aminu et al. (2023) also supported the validity of the EKC hypothesis in sub-Saharan African nations. Further, Li et al. (2024) constructed a model to test the existence of the EKC hypothesis in a panel of 38 countries. Their findings supported the EKC hypothesis, demonstrating a significant correlation between economic expansion and environmental degradation.

2.5. Nexus between trade openness and ecological sustainability

Numerous researchers have recently investigated the interconnection between TO and environmental excellence. Nonetheless, the conclusions of these studies are varied. For instance, Javed et al. (2023a) studied the relationship between TO and ecological sustainability in Italy, employing data from 1994 to 2018. Their empirical outcomes revealed that TO enhances environmental deprivation. In a recent study, Barkat et al. (2024) observed the linkage between TO and CO_2 emissions in 20 selected OECD nations. Their analysis revealed a significant positive association between TO and CO_2 emissions. Further, Musah et al. (2021) observed the TO and environmental quality linkage in D-8 countries, covering the time span from 1990 to 2016. For empirical analysis, they utilized the AMG and DCCEM approaches, and they observed that TO increased environmental hazards. Similarly, Al-Mulali and Ozturk (2015) inspected the role of TO on the environment in MENA countries, and they showed that TO enhanced environmental degradation. Contrary to this, Liu et al. (2022) looked into the TO and EF connection in Pakistan and observed a negative relationship. Moreover, Nathaniel et al. (2021) studied the correlation between TO and environmental health in N-11 countries. They discovered a positive impact of TO on degradation. Ahakwa et al. (2023) studied the impact of TO on the environmental quality of 89 BRI nations. Their findings revealed that TO boosts environmental sustainability in the underlying countries. Further, Wang et al. (2024b) examined the effect of TO on CO_2 emissions in OECD and G-20 countries. They demonstrated that TO harms environmental quality by increasing CO_2 emissions.

2.6. Nexus between urbanization and ecological sustainability

In recent years, there has been a growing correlation between urbanization and ecological health. However, these investigations have produced conflicting findings. For instance, some researchers have established that URB betters environmental health through the use of smart infrastructure, transportation, green energy, and other energy-efficient appliances, especially in developed countries (Balsalobre-Lorente et al., 2022; Zhou et al., 2022; Kang et al., 2016; Ulucak and Khan, 2020). Contrary to this, some other studies revealed a positive effect of URB on environmental deterioration (Javed and Rapposelli, 2022; Li et al., 2016; Kassouri, 2021; Pata, 2018; Farooq et al., 2022). Zhou et al. (2022) investigated the influence of URB on Pakistan's EFP from 1980 to 2018. They employed the dynamic simulated ARDL approach and revealed that URB significantly reduces the EFP. Further, Balsalobre-Lorente et al. (2022) explored the influence of URB on environmental betterment in BRICS economies from 1990 to 2014 and discovered that URB improves environmental health. In contrast, Pata et al. (2023) revealed an adverse effect of URB on the environment in the context of the USA. Similarly, Liu et al. (2024) suggested that urbanization generates an increase in human activity, which in turn leads to a rise in CO_2 emissions and deforestation, both of which contribute to a decline in the ecological equilibrium of a nation. Aziz et al. (2023) also investigated the impact of urbanization and natural resources on Saudi Arabia's CO_2 emissions. The study's outcomes revealed that urbanization is the main driving force behind Saudi Arabia's growing environmental degradation. Moreover, Nathaniel and Khan (2020) explored the connection between URB, TO, clean energy sources, and the EFP in ASEAN economies. Their empirical findings showed an insignificant impact of URB on the EFP. A detailed summary of the literature review is reported in Table 1.

2.7. Literature gap

After evaluating the existent literature, we concluded that the association between GTI, EP, and REN, along with important control variables in the incidence of the EKC hypothesis, has not yet been studied thoroughly, especially by taking into account the EFP as an indicator for environmental health in G-7 countries. Even though the aforementioned literature is a valuable source of knowledge for our research, it does have some limitations that need to be fulfilled. Therefore, the present study fills this gap by investigating the role of GTI, EP, and REN on ecological sustainability in G-7 economies. We also considered some important control variables, such as URB, TO, and GDP, to evaluate their impact on the EFP of G-7 countries. Further, previous studies on the G-7 economies have focused mostly on the connection between GTI, EP, and REN by considering only CO_2 emissions as a proxy of environmental health. However, a holistic perspective on climate change precludes discussing the issue solely regarding CO_2 emissions. Therefore, EFP is used in place of CO_2 emissions as a proxy for environmental quality in this investigation. The EFP accounts not only for the pollution caused by CO2 emissions but also for the other major contributors to environmental degradation due to human activity that humans are responsible for. For this reason, the EFP is seen as a good all-around measure of environmental health (Javed et al., 2023a). Moreover, the existing studies mostly utilized conventional mean estimators to analyze the relationship between the variables. However, these approaches provide inconsistent and misleading findings. Therefore, to avoid this issue, the present study utilized an advanced econometric approach, namely panel quantile regression (PQR), to scrutinize the effect of regressors on the various quantiles of the dependent variable (EFP). To the author's best understanding, no existing study in the background of G-7 countries has investigated the heterogenous impacts of GTI, EP, REN, GDP, GDP^2, TO, and URB on ecological sustainability by utilizing the novel PQR approach along with long-run mean estimators (FMOLS, DOLS, FE-OLS) and Dimitriscu-Hurlin panel granger causality test.

3. Theoretical mechanism, data, and methods

3.1. Theoretical underpinnings and model

The quality of the environment in which humans live and function is important for societal progress and economic advancement. Environmental factors have a direct influence on human health as well as the well-being of other living beings. A clean and healthy environment is vital for maintaining good health and productivity in human social interactions. Additionally, the natural resources of the environment, such as healthy living creatures and other valuable resources, play a critical role in implementing sustainable development plans and are integral to

Table 1
Literature summary.

Author(s)	Sample	Time Period	Methodology	Outcomes
Shan et al. (2021)	Turkey	1990–2018	ARDL, Granger causality	GTI, REN → CO_2 (−)
Sahoo and Sethi (2021)	Developing countries	1990–2016	FMOLS, DOLS	REN → EFP (−)
Li et al. (2022)	120 countries	1995–2014	Threshold Model	REN → EFP (−)
Usman and Hammar (2021)	(APEC) Asia Pacific Economic Cooperation	1990–2017	FGLS, AMG, CCEMG	TI, REN → EFP (−)
Destek and Sinha (2020)	24 OECD Countries	1980–2014	FMOLS-MG, DOLS-MG	TR, REN → EFP (−)
Nathaniel et al. (2021)	13 MENA Countries	1990–2016	FMOLS, DOLS	REN → EFP (−) GDP → EFP (+)
Zhang et al. (2022b)	E-5 countries	1990–2019	GMM, FMOLS	REN → EFP (−)
Danish et al., 2019	BRICS Economies	1992–2016	FMOLS, DOLS	REN → EFP (−)
Usman et al. (2020)	USA	1985Q1-2014Q4	ARDL, Granger causality	REN → EFP (−)
Adekoya et al. (2022)	14 Oil importing and exporting countries	1990–2014	AMG	REN → EFP (−)
Feng et al. (2022)	China	2011–2019	Benchmark regression	GTI → EFP (−)
Koseoglu et al. (2022)	20 green innovator economies	1993–2016	Bootstrap Cointegration	GTI → EFP (−) GDP → EFP (+)
Liu et al. (2022)	10 Asian economies	2005–2020	DOLS, FMOLS	GTI, GIT → EFP (−)
Ke et al. (2022)	China	2008–2018	OLS, DMSP	GIT → EFP (−)
Chu (2022)	20 OECD economies	1990–2015	GMM, OLS, FGLS	GTI, TR → EFP (−)
Kihombo et al. (2021)	West and Middle east countries	1990–2017	GMM, FE, RE	TI → EFP (−)
Usman and Radulescu (2022)	Top Nuclear energy producing economies	1990–2019	AMG	TI → CFP (+) REN → EFP (−)
Sherif et al. (2022)	N-11 economies	1992–2015	VECM, FMOLS	TI → EFP (−)
Destek and Manga (2021)	BEM Countries	1995–2016	CUP-BC, CUP-FM	REN, TI → EFP, CO_2 (−)
Zeraibi et al. (2021)	5-ASEAN economies	1985–2016	CS-ARDL Model	REN, TI → EFP, CO_2 (−)
Rafique et al. (2022)	29 OECD economies	1994–2016	ARDL, DOLS, FMOLS, PMG	EP → EFP (−)
Telatar and Birinci (2022)	Turkey	1994–2019	Nonlinear Model	EP → Not effected to EFP, CO_2
Fang et al. (2023)	China	2010–2020	PSTR Model	EP → EFP (−)
Ullah et al. (2023)	Top 7 green countries	1995Q1-2018Q4	Quantile-on-Quantile Approach	EP → EFP (−)
Nathaniel and Adedoyin (2020)	MINT Economies	1980–2016	FMOLS	EP → EFP (−)
Chu and Tran (2022)	27 OECD economies	1990–2015	Quantile Regression	EP → EFP (−)
Doğan et al. (2022)	G-7 countries	1994–2014	FMOLS	EP → CO_2 (−)
Tao et al. (2021)	Emerging 7 countries	1995–2018	CS-ARDL	EP → CO_2 (−)

Notes: GTI = Green technological innovation, EP = Environmental policy, REN = Renewable energy, EFP = Ecological footprint, CO_2 = Carbon emission, TI = Technological innovation, → = Represents.

the current economic processes. However, the integrity of these resources and the nation's overall development are negatively impacted by the pollution resulting from various human social and economic activities. Studies organized by Bekun et al. (2019), Chien et al. (2022), and Xiang et al. (2021) demonstrate that CO_2 emissions are one of the most damaging factors to the environment. The presented literature background has analyzed ecological footprints, but a dearth of studies have explored the GTI, EP, REN, GDP, TO, and URB, particularly in G-7 countries. Our theoretical framework is based on the EKC and the double-dividend hypothesis of environmental policy (Dinda, 2005). In theory, an upsurge in the consumption of resources results in an intensification of the ecological deficit and ecological footprint.

The attainment of sustainability and resolution of the aggravated issue of EFP hinges on sustainable choices (Ahmed et al., 2019). Indeed, it has been acknowledged that adopting and developing green technologies are essential for reducing environmental deterioration and attaining ecological sustainability. Previous literature showed that GTI has a negative association with environmental degradation $\boldsymbol{\beta_1} = \frac{\beta EFP_{i,t}}{\beta GTI_{i,t}} < \mathbf{0}$, and the expected sign for this variable is negative (−). Green technologies refer to innovations that aim to reduce negative environmental impacts and increase resource efficiency. These technologies range from renewable energy sources to sustainable agriculture practices and eco-friendly manufacturing processes. Further, green technologies can facilitate the transition towards sustainable development by reducing environmental risks, enhancing resource productivity, and promoting the development of low-carbon economies (Wu et al., 2020; Luo et al., 2019). In addition, GTI can create new business opportunities and employment, as well as improve the standard of living through access to cleaner and safer environments (Lin et al., 2018). Overall, the adoption and development of GTI can considerably enhance environmental quality or performance and achieve environmental sustainability while promoting economic growth and development.

Utilizing eco-friendly products, reducing production and consumption, and putting end-of-pipe abatement strategies into practice are just a few strategies that can be used to reduce environmental pollution. An effective environmental policy can enhance the effectiveness of these measures by limiting the use of environmentally damaging goods and practices through increased costs, as well as encouraging eco-friendly technology and products through subsidies and security. These pollution reduction strategies can be augmented through an environmental policy, as suggested by research conducted by Guo et al. (2021) and Rafique et al. (2022). There is a substantial adverse relationship between the implementation of environmental policy (EP) and environmental degradation $\boldsymbol{\beta_2} = \frac{EFP_{it}}{\beta EP_{i,}} < \mathbf{0}$, and the expected sign for this variable is negative (−)This is due to the effectiveness of environmental policies as a government tool for eliminating environmental degradation (Bashir et al., 2020). The fundamental aim of EP is to impose emission taxes to encourage improved energy efficiency, mitigate environmental concerns, and contribute to environmental conservation by incorporating adverse externalities such as environmental pollution (Kou et al., 2021; Shahzad, 2020; Bashir et al., 2021). Specifically, environmental policies are particularly advantageous for goods that consume scarce natural resources. Environmental policies can effectively target market deficiencies that result in the environment-related outcomes of economic activities being overlooked (Rafique et al., 2022). An appropriately developed environmental policy ensures that the prices of goods or activities reflect the expenses related to the harm caused to the environment and others (OECD, 2011).

However, apart from restricting the usage of resources, transitioning human actions from fossil fuels to renewable energy resources is another strategy to enhance sustainability. Prior studies indicate that there exists an inverse relation between the REN and EFP like $\boldsymbol{\beta_3} = \frac{\beta EFP_{i,t}}{REN_{it}} < \mathbf{0}$ and the expected sign for this variable is negative (−). This can be attributed to the fact that fossil fuels have contributed to global environmental degradation, and there is now a growing focus on sustainable development that relies on cleaner and renewable energy sources (Elum and Momodu, 2017). In addition, it is worth noting that renewable energy is crucial for domestic production and investment and necessary for mitigating the country's environmental impact. It has been advocated that transitioning from centralized non-renewable energy generation to a decentralized system using renewable energy can also positively influence the climate by lowering CO_2 emissions and EFP (Sharif et al., 2020). Further, renewable energy is considered an important factor in developing economically efficient and technically feasible strategies to reduce environmental hazards and increase ecological balance (Gyamfi et al., 2018). Using renewable energy sources can reduce air pollution, enhance energy security, and decrease dependence on fossil fuels (Al-Mulali et al., 2016). Furthermore, adopting REN can lead to reduced energy costs, better air quality, improved human health, job creation, and mitigation of environmental and climate impacts.

In addition, our model includes control variables following earlier research. Given that economic growth typically results in environmental harm (Ma et al., 2019; Neagu, 2020; Javed et al., 2023b), we expect it will positively impact the EFP. The EFP is primarily a result of heightened demand for resources, energy utilization, and economic expansion driven by population growth and their essential requirements for sustenance, clothing, and housing (Nathaniel et al., 2019; Zhang et al., 2017). Moreover, GDP and EFP are positively correlated and have a close relationship $\beta_4 = \frac{\boldsymbol{\beta EFP_{i,t}}}{\boldsymbol{\beta GDP_{i,t}}} > \mathbf{0}$; the expected sign for this variable is positive (+). This is because enhanced economic activity leads to increased output, which heightens energy consumption, decreases environmental quality, and causes adverse environmental impacts. This suggests, in line with other research, that GDP is expected to positively affect environmental degradation (Destek and Sarkodie, 2019; Ding et al., 2021; Hao et al., 2021). Similarly, the influence of economic activities on environmental deterioration has become a prevalent area of study. The EKC hypothesis has been the most extensively researched theory on the connection between income levels and environmental quality. The EKC hypothesis suggests that environmental degradation rises in the early or initial stages of economic developmen, but declines after reaching a certain inflection point, leading to an inverted U-shaped connection between advancing economic conditions and deteriorating environmental conditions (Destek and Sarkodie, 2019; Saidi and Mbarek, 2017; Sarkodie, 2018). The results suggest that GDP^2 and EFP are negatively related $\boldsymbol{\beta_5} = \frac{\boldsymbol{\beta EFP_{i,t}}}{\boldsymbol{\beta GDP^2_{i,t}}} < \mathbf{0}$ and the expected sign for this variable is positive (−).

The role of trade openness on the environment has been a topic of debate. TO may increase production activities and energy consumption, resulting in environmental pollution (Shahbaz et al., 2017). However, trade liberalization can also generate wealth and improve living standards, which may help reduce poverty, a significant contributor to environmental humiliation. The impact of TO on environmental degradation varies across economies, likely due to differences in policies, economic structures, levels of openness, and other country-specific factors (Baek et al., 2009; Naranpanawa, 2011; Wiebe et al., 2012; Forslid and Okubo, 2015). Thus, TO reduces the efficiency of the EFP $\boldsymbol{\beta_6} = \frac{\boldsymbol{\beta EFP_{i,t}}}{\boldsymbol{\beta TO_{i,t}}} > \mathbf{0}$ and the expected sign for this variable is positive (+).

Most of the earlier studies attribute urbanization, which leads to the formation of considerable consumer markets, to being one of the key drivers of EFP. Additionally, it amplifies the human need for bioproductive elements in their production and consumption activities (Nathaniel et al., 2020). Environmental deterioration has been correlated with higher economic development and various developmental indicators (Alper and Oguz, 2016; Ahmad et al., 2016). This is especially important in emerging nations with a rising urban population trend that is changing the quality of the environment (Sassen, 1991). The population's composition varies as development intensifies, posing opportunities and risks to the environment. Both theoretical and empirical investigations have made significant progress in understanding how URB affects the environment (Liddle and Lung, 2010). Despite this, other studies contend that urbanization can improve environmental quality if clean technology is used, the energy mix is modernized, and institutional support is provided (York et al., 2003). By using methods that are optimized for urban settings, resources can be used more effectively while waste is reduced (Charfeddine, 2017). Additionally, according to the ecological modernization theory, by fostering clean technology and effective use, the scale and rate of production and income can help counteract the detrimental effects of urbanization on environmental degradation. These mechanisms spotlight the fact that URB may either promote or inhibit EFP $\boldsymbol{\beta_7} = \frac{\boldsymbol{\beta EFP_{i,t}}}{\boldsymbol{\beta URB_{it}}} < \mathbf{0}$ **or** $> \mathbf{0}$, and the expected sign for this variable can be negative (−) or positive (+). Fig. 5 presents a summary of the expected relationship between the explained (EFP) and the explanatory factors of the study (GTI, EP, REN, GDP, GDP^2, TO, and URB).

This study developed the following model based on the aforementioned theoretical background:

$$EFP_{it} = f\left(GTI_{it}, EP_{it}, REN_{it}, GDP_{it}, GDP^2_{it}, TO_{it}, URB_{it}\right) \tag{1}$$

where the following is the regression from the specified model:

$$EFP_{it} = \alpha_o + \beta_1 GTI_{it} + \beta_2 EP_{it} + \beta_3 REN_{it} + \beta_4 GDP_{it} + \beta_5 GDP^2_{it} + \beta_6 TO_{it} + \beta_7 URB_{it} + \varepsilon_{it} \tag{2}$$

The focus variables in Eq. (2) are GTI, EP, and REN, while GDP, GDP^2, TO, and URB are controlled variables. The estimated coefficients are represented by β_1 to β_7, and α represents the intercept. The index "i" refers to the cross-sectional unit (in this study, G-7 countries), while "t" represents the time series index. The error term of the model is denoted by $\varepsilon_{i,t}$.

3.2. Data

The present study aims to empirically investigate the impact of green technology innovation (GTI), environmental policy (EP), renewable energy consumption (REN), trade openness (TO), urbanization (URB), and gross domestic product (GDP) on the ecological footprint (EFP) in the presence of the EKC hypothesis in G-7 countries. For analysis, we utilize the panel data set of these countries from 1994 to 2018, based on the availability of the data. The main variable of the study is EFP, measured as global hectares per capita. The explanatory variables of the study include green technology innovation, measured as environmental related technologies percentage of all technologies; environmental policy, expressed as environmental taxes percentage of GDP; renewable energy consumption, expressed as a percentage of total final energy consumption; trade openness, defined as percentage of GDP; urbanization, defined as urban population percentage of total population; and gross domestic product, measured at constant 2015 US$ per capita. The statistics for GTI and EP are retrieved from the OECD database, while those for REN, TO, URB, and GDP are sourced from the World Bank. Table 2 presents the research variables symbols, units of measurement, and data sources. Further, Fig. 6 provides a visual representation of the geographic positioning of the G-7 countries.

3.3. Estimation strategy

When dealing with panel data, it is essential to investigate the nature and characteristics of the data first. The results of the diagnostic tests are then used to determine which econometric tests will be most appropriate and practical. The current study considers the advanced econometric approaches to investigate the effect of independent variables (GTI, EP, REN, GDP, $GDP^{2,}$ TO, and URB) on the explained variable (EFP). Our study's econometric strategy consists of six steps (see Fig. 7). In the *first step* of the estimation process, the parameters slope coefficient

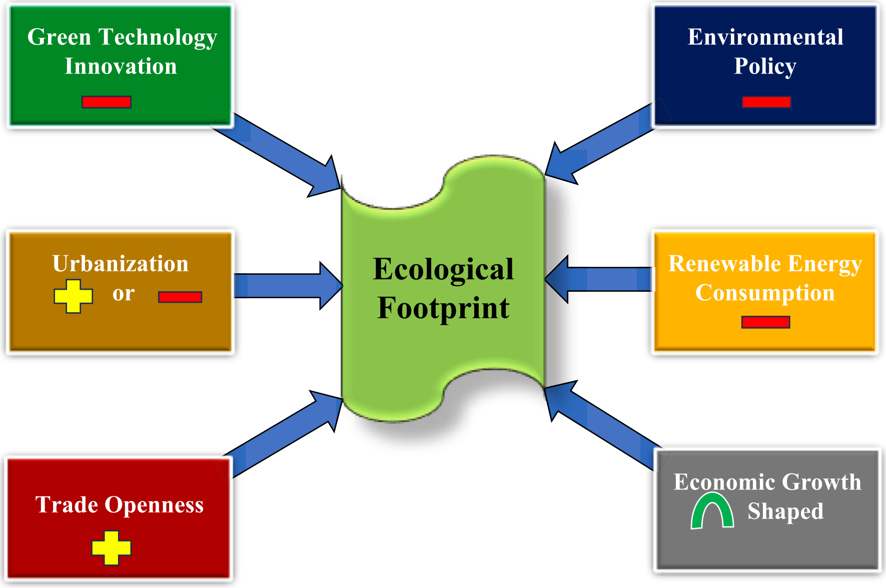

Fig. 5. Expected association between the independent and dependent variables.
(Source: Authors own creation)

Table 2
Variables description.

Variables	Measurement unit	Sources
EFP	Ecological footprint per capita (global hectares)	GFN
GTI	Environmental-related technologies % of total technologies	OECD
EP	Environment-related taxes (% of GDP)	OECD
REN	Renewable energy consumption (% of total final energy consumption)	WDI
GDP	Gross Domestic Product (constant 2015 US$) per capita	WDI
TO	The ratio of exports plus imports over GDP (%)	WDI
URB	Urban population (% of total population)	WDI

heterogeneity (SCH) is tested by utilizing the Pesaran and Yamagata (2008) test. In the *second step,* the cross-sectional dependency is checked using the Pescaran cross-sectional dependency test (Pesaran, 2007). The stationarity properties of the underlying variables are evaluated in the *third step* by performing the 2nd-generation stationarity test, namely cross-sectional augmented Im, Pesaran, and Shin (CIPS). In the *fourth step*, the long-run cointegration association among the variables is confirmed by employing the cointegration test of Westerlund's (2007) cointegration test. In the *fifth step*, the long-term connections between variables are observed using the FMOLS, DOLS, FE-OLS, and Panel Quantile Regression (PQR) techniques. In the *final step*, the causality direction among the variables under investigation is investigated employing the panel Granger causality test (Dumitrescu and Hurlin, 2012).

3.3.1. *Slope coefficient heterogeneity*

In the *first estimation step*, we investigated the nature of slope coefficients. Traditional estimators in panel data analysis assume slope coefficient homogeneity in the panel data set. As a result, these tests provide biased and misleading outcomes by being unable to address the slope coefficient heterogeneity issue. To avoid deceptive outcomes, the present research examined the slope coefficient heterogeneity by using the Pesaran and Yamagata (2008) slope heterogeneity test. This test is reliable because it provides standard and adjusted SCH estimates. The estimates of SCH and adjusted SCH can be calculated as follows:

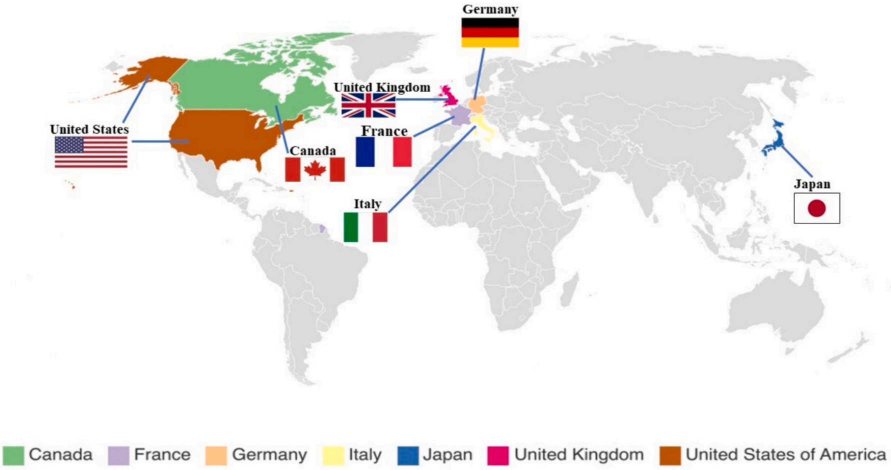

Fig. 6. Geographical coverage of the G-7 nations.
(Source: Authors own creation)

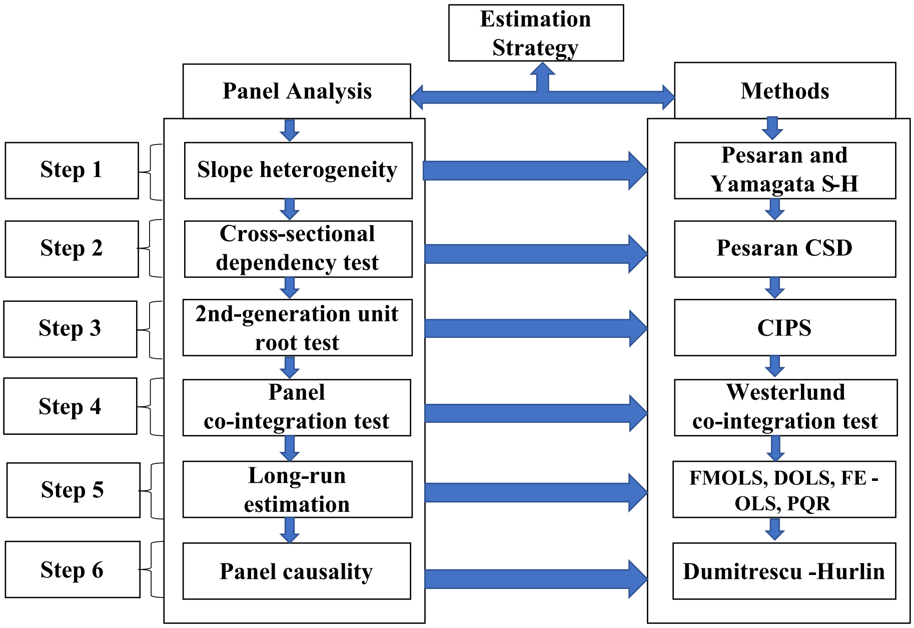

Fig. 7. Flow chart of estimation strategy.
(Source: Authors own creation)

$$\widetilde{\Delta} sch = (N)^{1/2}(2K)^{-(1/2)}\left(\frac{1}{N}\widetilde{S} - K\right) \tag{3}$$

$$\widetilde{\Delta} Adj - sch = (N)^{1/2}\left(\frac{2K(T-K-1)}{T+1}\right)^{-1/2}\left(\frac{1}{N}\widetilde{S} - 2K\right) \tag{4}$$

In Eq. (3), the slope coefficient homogeneity is denoted by SCH, and the adjusted slope homogeneity is denoted by ADJ-SCH in Eq. (4). The H0 of slope coefficient homogeneity is verified against the H_1 of slope coefficient heterogeneity.

3.3.2. Cross-sectional dependency CSD test

In the next step, the CSD among the cross-sections is analyzed before empirical analysis of the connections between the factors under consideration. The CSD is a major issue in the panel data analysis that may lead to a serious problem with selecting an appropriate stationarity test, cointegration test, and econometric model. As a result, CSD among the panels can cause misleading findings if an appropriate econometric instrument is not used. For this purpose, we used the Pesaran (2007) CSD test to evaluate the CSD. The equation of CSD is given as:

$$CSD = \sqrt{\frac{2T}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} T_{ij} \tag{5}$$

In the above equation, T_{ij} denotes the parameters pair-wise correlation, N symbolizes the cross-sections, and T depicts the time period.

3.3.3. Panel stationarity test

In the occurrence of CSD and SCH, first-generation stationarity tests may provide inaccurate results (Baltagi et al., 2016). Thus, CSD and SCH are important in determining the appropriate stationarity test. Therefore, the present research used Pesaran's (2007) CIPS test to evaluate the stationarity characteristics of the underlying variables. This test deals with the issues of both CSD and SCH. Hence, this test is more suitable than the first-generation unit root tests. The equation of the test is as follows:

$$\widehat{CIPS} = N^{-1}\sum_{i=0}^{n} CDF_i \tag{6}$$

3.3.4. Panel cointegration test

After confirming the variables' stationarity, the next task is to look for evidence of a long-term cointegration relationship between GTI, EP, REN, GDP, TO, URB and EFP in all G-7 countries. The present research used the cointegration test developed by Westerlund (2007) to verify the existence of long-term cointegration among the study's parameters. As compared to the traditional cointegration tests by Kao (1999) and Pedroni (2004), this cointegration test provides robust and reliable outcomes due to its ability to consider CSD problems and parameter slope heterogeneity (Persyn and Westerlund, 2008). The mathematical formulation of the model is as follows:

$$G_t = \frac{1}{N}\sum_{i=1}^{N}\frac{\alpha_i}{SE(\alpha_i)} \tag{7}$$

$$G_a = \frac{1}{N}\sum_{i=1}^{N}\frac{T\alpha_i}{\alpha_i(1)} \tag{8}$$

$$P_t = \frac{\alpha}{SE(\alpha)} \tag{9}$$

$$P_t = T\alpha \tag{10}$$

Eqs. (7) and (8) represent the two group mean (Ga and Gt) statistics, while Eqs. (9) and (10) indicate the two panel (Pa and Pt) statistics. The H_0 of the absence of cointegration is assessed against the presence of cointegration.

3.3.5. Panel quantile regression

In the *fourth step*, we proceed by applying the long-run panel mean estimation approaches of Pedroni's (2001) Fully Modified Ordinary Least Square (FMOLS), Stock and Watson's (1993) Dynamic OLS (DOLS), and Fixed Effect OLS (FE-OLS) to evaluate the mean effects of GTI, EP, REN, GDP, GDP^2, and TO on EFP in G-7 countries. However, the issue with these traditional estimators is that they emphasize the average effects of the diverse panels and yield mean estimates, which can result in underestimating or overestimating the relevant coefficients or failing to identify the significant relationships. Thus, to address the limitations of the long-run panel mean estimation approaches, Koenker and Bassett Jr (1978) advanced the panel quantile regression (PQR) approach, which is applied by many researchers in the existing literature (Zhu et al., 2016; Salman et al., 2019; Cheng et al., 2019; Ahmad and Wu, 2022; Wang et al., 2023). The PQR approach gauges the heterogeneous impacts of the explanatory variables by considering the various levels (quantiles) of the explained variable (EFP). The specification of the PQR, based on Eq. (11), is as follows:

$$Q_{EFP_{i,t}}(\tau/X_{i,t}) = \varphi_i^{(\tau)} + \varphi_1^{\tau}GTI_{i,t} + \varphi_2^{\tau}EP_{i,t} + \varphi_3^{\tau}REN_{i,t} + \varphi_4^{\tau}GDP_{i,t} + \varphi_5^{\tau}GDP_{i,t}^2 + \varphi_6^{\tau}TO_{i,t} + \varphi_7^{\tau}URB_{i,t} + \varepsilon_{i,t} \tag{11}$$

where $Q_{EFP_{i,t}}(\tau/X_{i,t})$ represents the conditional quantile τ^{th} of the dependent variable $EFP_{i,t}$, while $X_{i,t}$ is the vector of the independent variables (GTI, EP, REN, GDP, GDP^2, TO, and URB). Further, φ_s' coefficients of the slope parameters of cause variables for τ^{th} quantile.

Next, we conduct a test to evaluate the equality of the coefficients of the slope parameters. This test helps us to learn if there is any difference in the slope coefficients between the quantiles. For instance, if two quantile regression equations are supplied, like in the case of the inter-quantile regression between $\tau = 0.10$ and 0.30,

$$Q_{0.10}(EPC_{i,t}) = \varphi_{0.10} + \varphi_{0.10,1}GTI_{i,t} + \varphi_{0.10,2}EP_{i,t} + \varphi_{0.10,3}REN_{i,t} + \varphi_{0.10,4}GDP_{i,t} + \varphi_{0.10,5}GDP_{i,t}^2 + \varphi_{0.10,6}TO_{i,t} + \varphi_{0.10,7}URB_{i,t} + \varepsilon_{i,t} \tag{12}$$

$$Q_{0.30}(EPC_{i,t}) = \varphi_{0.30} + \varphi_{0.30,1}GTI_{i,t} + \varphi_{0.30,2}EP_{i,t} + \varphi_{0.30,3}REN_{i,t} + \varphi_{0.30,4}GDP_{i,t} + \varphi_{0.30,5}GDP_{i,t}^2 + \varphi_{0.30,6}TO_{i,t} + \varphi_{0.30,7}URB_{i,t} + \varepsilon_{i,t} \tag{13}$$

We may calculate the inter-quantile difference (between 0.10 and 0.30) by subtracting Eq. (12) from Eq. (13) as follows:

$$Q_{0.30}(EPC_{i,t}) - Q_{0.10}(EPC_{i,t}) = (\varphi_{0.30} - \varphi_{0.10}) + (\varphi_{0.30} - \varphi_{0.10})GTI_{i,t} + (\varphi_{0.30} - \varphi_{0.10})EP_{i,t} + (\varphi_{0.30} - \varphi_{0.10})REN_{i,t} + (\varphi_{0.30} - \varphi_{0.10})GDP_{i,t}^2 + (\varphi_{0.30} - \varphi_{0.10})TO_{i,t} + (\varphi_{0.30} - \varphi_{0.10})URB_{i,t} + \varepsilon_{i,t} \tag{14}$$

Using the Wald test to establish slope equality across quantiles, we may estimate the inter-quantiles of parameter slope coefficients, as shown in Eq. (14). For each quantile, we examine the equality of slope under the H_0 of slope equality when $\tau = 0.10$.

3.3.6. *Panel Granger causality test*

In the *final step*, we inspect the causal relationship between the EFP and the other explanatory variables. The aforementioned methodologies, such as FMOLS, DOLS, FE-OLS, and PQR approaches, only give the particular impact of the independent variables on the dependent variable and overlook the causal association among the variables. The present study employed the pairwise panel Granger causality test of Dumitrescu and Hurlin (2012). This causality test accommodates the CSD and SCH issues and provides robust outcomes even if the panel is unbalanced (Banday and Aneja, 2020). The general formulation of this test is expressed as follows:

$$Z_{i,t} = \sigma_i + \sum_{k=1}^{p}\alpha_i^k Z_{i,t-k} + \sum_{k=1}^{p}\psi_i^k T_{i,t-k} \tag{15}$$

where i represents the lag length, $\alpha^k(K)$ is a representation of the autoregressive coefficients, i is the cross-section, and t is the time dimension of data, respectively. This test compares the absence of homogeneous causality (null hypothesis) against the presence of heterogeneous causality (the alternative).

4. Results and discussion

4.1. *Results*

Before proceeding with the empirical analysis, we carefully examine the descriptive analysis to better understand the variables' characteristics. Table 3 displays these descriptive characteristics. The highest mean value is revealed for GDP (10.531), followed by URB (4.357), TO (3.834), GTI (2.246), REN (1.964), EFP (1.798), and EP (0.600), respectively. According to the skewness value, EFP and GDP are positively skewed, whereas GTI, EP, REN, TO, and URB are all negatively skewed. Additionally, the kurtosis parameter reveals that REN and URB exhibit leptokurtic distributions, while EFP, GTI, EP, GDP, and TO show platykurtic distributions. Further, the Jarque-Bera test indicates that all the research variables do not satisfy the assumption of normality. Thus, Jarque-Bera test results reveal that using the linear estimator may provide misleading outcomes. Therefore, this study employed the PQR technique to determine the interconnections between the explained and explanatory factors. Further, Fig. 8 displays the box-plot summary statistics of the underlying variables.

Further, to evaluate the heterogeneity issue, we used the Pesaran and Yamagata (2008) slope heterogeneity test, and the statistics are shown in Table 4. These results illustrate that our research model has a problem with SCH. The significant values of delta and adjusted delta demonstrate the heterogenous slopes. The results support the alternative hypothesis, and the null of no heterogeneity is rejected at the 1 % significance level. Next, cross-sectional dependency is the most frequent problem with panel data analysis, and it needs to be fixed before looking at the connection among the variables (Salim et al., 2017). We conducted the CSD test (Pesaran's, 2007) to avoid this problem; the findings are presented in Table 5. The outcomes disclose that H_0 of "cross-sectional independence" is rejected against the alternative, confirming the data's CSD. Thus, any shock in GTI, EP, REN, GDP, TO, URB, and EFP in individual G-7 countries will be transmitted to other G-7 countries. Consequentially, it is evident that the G-7 countries are highly interconnected.

Both slope heterogeneity and cross-sectional dependence test results confirm the presence of CSD and SCH. The existence of CSD and SCH has been confirmed by tests. Due to CSD and SCH issues, the traditional stationarity tests advanced by Levin et al. (2002) and Im et al. (2003) provide unreliable results and necessitate using the 2nd-generation stationarity tests. For this purpose, the present research used the CIPS unit root test developed by Pesaran (2007). This test produces efficient estimates even when CSD and SH issues occur. The outcomes of the CIPS test are given in Table 6. The results show that all the underlying variables are stationary at I(1). These results reject the H_0 of a unit root in favour of the alternative hypothesis of stationarity. Next, the current study used the cointegration technique put forward by Westerlund (2007) to validate the long-term connections among the study variables. Table 7 reports the outcomes of the cointegration test. The estimated outcomes reject the H_0 of no "long-term cointegration" against the H_1 of the presence of "long-term cointegration". These statistics prove that GTI, EP, REN, GDP, TO, and URB in G-7 countries have a long-term cointegrating relationship with their EFP over time.

This study investigates the long-run impact of GTI, EP, REN, GDP, GDP^2, TO, and URB on ecological sustainability by employing three long-run panel mean estimation approaches: FMOLS, DOLS, and FE-OLS. The findings of all three models are reported in Table 8. The

Table 3
Descriptive statistics.

	EFP	GTI	EP	REN	GDP	TO	URB
Mean	1.798	2.246	0.600	1.964	10.531	3.834	4.357
Median	1.707	2.282	0.775	2.016	10.487	3.954	4.364
Maximum	2.336	2.754	1.281	3.122	10.995	4.482	4.518
Minimum	1.430	1.627	−0.315	−0.163	10.256	2.761	4.203
Std. dev.	0.259	0.290	0.426	0.818	0.177	0.424	0.072
Skewness	0.731	−0.330	−0.510	−0.665	0.727	−0.711	−0.274
Kurtosis	2.206	2.017	2.242	3.146	2.663	2.499	3.514
Jarque-Bera	20.171	10.218	11.785	13.046	16.226	16.585	4.130
Probability	0.000	0.006	0.002	0.001	0.000	0.000	0.002
Observations	175	175	175	175	175	175	175

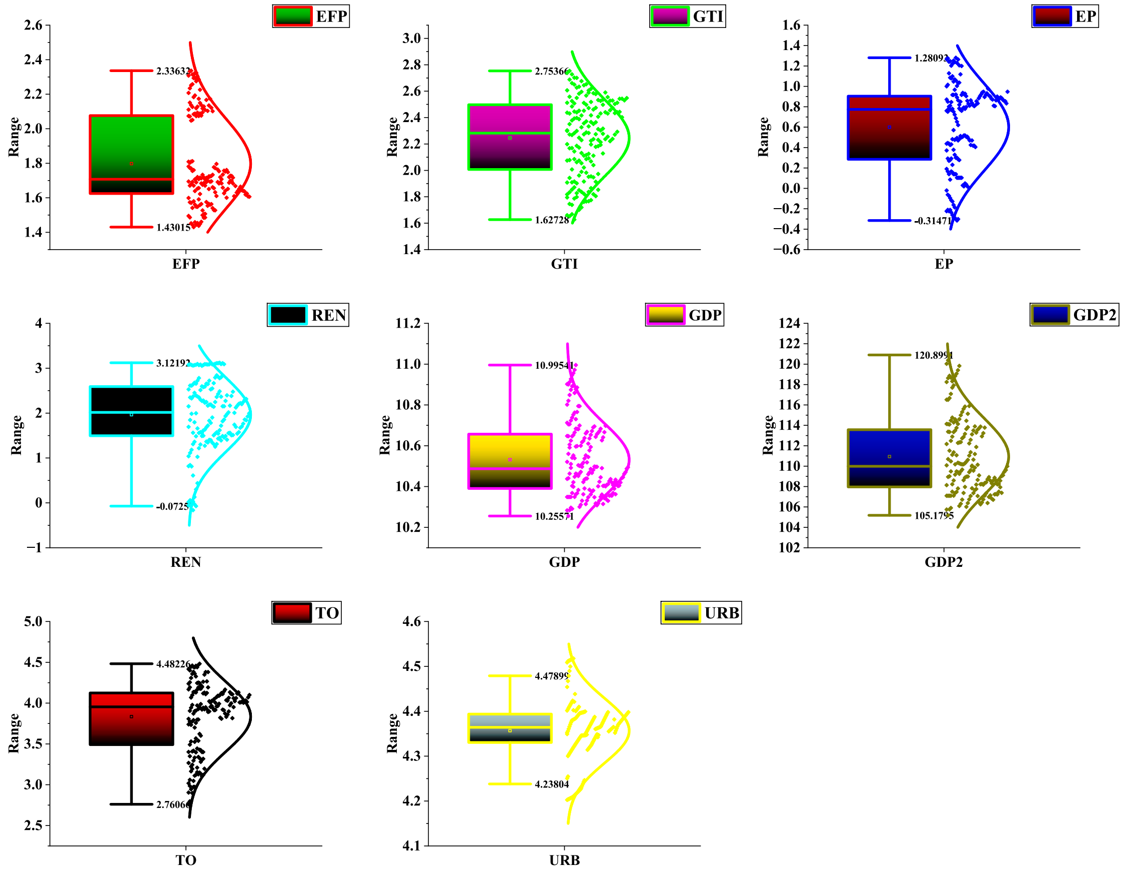

Fig. 8. Box-plot summary descriptive statistics of variables.

Table 4
Slope heterogeneity test results.

Test	Statistic	Prob.
$\widetilde{\Delta}$	6.811***	0.000
$\widetilde{\Delta}$ adjusted	8.514***	0.000

Note: *** specifies a significance level of 1 %.

Table 5
Cross-sectional dependence test results.

	Pesaran CSD	*P*-value
EFP	9.817***	0.000
GTI	10.129***	0.000
EP	7.982***	0.000
REN	5.148***	0.000
GDP	7.838***	0.000
TO	5.503***	0.000
UR	7.289***	0.000

Note: *** indicates the significance level at the 1 % level.

outcomes illustrate that GTI has a significant adverse effect on the EFP in all three models at the 1 % significance level, provided that development in GTI minimizes environmental degradation by lowering the EFP and, as a result, improves ecological sustainability in G-7 countries. This negative significant effect of GTI on EFP concludes that holding all other parameters constant, a 1 % rise in GTI reduces the EFP by 0.049 (FMOLS) ~ 0.067 (DOLS) and 0.322 (FE-OLS), respectively. Secondly, the environmental policy also exerts an advantageous impact on the reduction of EFP at a significance level of 1 % in all three models and contributes to ecological sustainability in G-7 economies. The statistics show that a 1 % rise in EP diminishes the EFP by 0.196 (FMOLS) ~ 0.254 (DOLS) and 0.768 (FE-OLS), respectively. This suggests that EP is beneficial for the quality of the environment. Further, the outcomes suggest that the impact of REN on EFP is significantly negative in all

Table 6

Unit root test results (Pesaran, 2007).

Variables	Intercept and trend	
	I(0)	I(1)
EFP	−2.740***	−4.717***
GTI	−3.415***	−4.754***
ET	−1.898	−4.109***
REN	−2.232*	−5.263***
GDP	−1.551	−2.730***
TO	−1.773	−3.687***
UP	−2.334	−3.196***

Note: * and ** indicate the significance level at 1 % and 5 %, respectively.

Table 7

Cointegration results (Westerlund, 2007).

Statistic	Value	*Z*-value	Robust P-value
Gt	−3.945***	−3.054	0.000
Ga	−4.691*	3.681	0.080
Pt	−9.302***	−2.309	0.000
Pa	−5.044*	2.432	0.072

Note: *** and * explain the significance level at 1 % and 10 %.

Table 8

Long-run mean estimates.

Variables	FMOLS		DOLS		FE-OLS	
	Coefficient	Std. error	Coefficient	Std. error	Coefficient	Std. error
GTI	−0.049***	0.010	−0.067***	0.036	−0.061**	0.026
EP	−0.196***	0.025	−0.254***	0.087	−0.189***	0.065
REN	−0.087**	0.005	−0.052**	0.022	−0.084***	0.013
GDP	22.532**	1.365	20.555***	5.254	20.659***	3.374
GDP^2	−1.065***	0.065	−0.976***	0.250	−0.975***	0.160
TO	0.077***	0.016	0.078***	0.060	0.067*	0.419
URB	−1.589***	0.089	−1.435**	0.289	−1.547***	0.233

Note: ***, **, and * represent the significance levels at 1 %, 5 %, and 10 %, respectively.

three approaches. The estimated parameters of REN show that a 1 % upsurge in REN is related to a decline in EFP of 0.087 (FMOLS) ~ 0.052 (DOLS) and 0.018 (FE-OLS), respectively. This negative connection between REN and EFP indicates that REN utilization promotes ecological sustainability.

Turning to the case of GDP, the findings reveal a significant positive effect on environmental degradation in all the regression models, which denotes that keeping the remaining variables constant, a 1 % rise in GDP tends to raise the EFP by 22.532 (FMOLS), 20.555(DOLS), and 21.937 (FE-OLS), respectively. Moreover, GDP^2 has a negative significant impact on the EFP. Based on the magnitude, a 1 % rise in GDP^2 reduces the level of EFP by 1.065 (FMOLS), 0.976 (DOLS), and 1.035 (FE-OLS), accordingly. This significant negative coefficient value of GDP^2 confirms the validity of EKC in all three models. Further, TO discloses a positive influence on the EFP in all three models, revealing that a rise in trade activities damages the environment by lifting the level of EFP in the examined countries. The estimated parameter magnitude of TO suggests that keeping the other variables constant, a 1 % increase in trade openness enhances environmental degradation by 0.077 (FMOLS), 0.078(DOLS), and 0.188 (FE-OLS). The computed outcomes also establish a negative correlation between URB and EFP in all the regression models. As a 1 % growth in URB reports, the reduction in EFP is 1.589 (FMOLS), 1.435 (DOLS), and 1.622 (FE-OLS), respectively.

After assessing the relationship between the examined variables through the three different long-run mean estimation models, we proceed to gauge the heterogeneous effects of GTI, EP, REN, GDP, GDP^2, TO, and URB on ecological sustainability across different quantiles spanning from 10th to 90th by employing a novel approach, namely the PQR approach. Table 9 reports the findings of PQR. The estimates of PQR depict the heterogeneous impact of GTI, EP, REN, GDP, GDP^2, TO, and URB on ecological sustainability at various quantiles (0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, and 0.90). We provide the estimated effects of the independent variables at the various quantiles of the dependent variable (EFP). We have split the quantile distribution into three groups, from lowest ($\tau =$ from 0.10 to 0.30), to middle ($\tau =$ from 0.40 to 0.60), to highest quantiles ($\tau =$ from 0.70 to 0.90) to better facilitate the interpretations of our results. The following are the empirical outcomes obtained by PQR: First, the results reveal that the effect of GTI on EFP is negative and statistically significant across all quantiles, indicating that GTI reduces EFP at each quantile and, as a result, promotes environmental sustainability. However, this effect varies across all the quantiles, as shown in Fig. 9.

Further, at different quantiles, environmental policy depicts a significant adverse influence on the EFP. The effect size varies from the lowest to the upper quantiles (see Fig. 9). It implies that EP enhances ecological sustainability by decreasing the EFP in the underlying countries. Next, the estimated results disclose a significant negative impact of REN on EFP across all quantiles. However, REN failed to reflect any significant effect at the 10th quantile. Moreover, the magnitude of the effect is getting larger at the upper quantiles. This entails that using REN boosts the environmental health of G-7 countries.

Table 9

Panel quantile regression results.

Dependent variable: EFP									
Variables	Quantile								
	Q10	Q20	Q30	Q40	Q50	Q60	Q70	Q80	Q90
GTI	−0.345***	−0.310***	−0.316***	−0.284***	−0.301***	−0.274***	−0.277***	−0.254***	−0.280***
	(0.918)	(0.056)	(0.048)	(0.046)	(0.038)	(0.033)	(0.036)	(0.035)	(0.037)
EP	−0.652***	−0.748***	−0.746***	−0.729***	−0.714***	−0.765***	−0.797***	−0.861***	−0.878***
	(0.106)	(0.048)	(0.044)	(0.051)	(0.048)	(0.046)	(0.046)	(0.045)	(0.043)
REN	0.009	−0.018***	−0.013**	−0.010***	−0.021**	−0.019***	−0.020***	−0.034**	−0.058***
	(0.028)	(0.015)	(0.012)	(0.016)	(0.015)	(0.012)	(0.013)	(0.015)	(0.019)
GDP	29.988**	28.124***	30.419***	32.068***	30.705***	25.206***	20.396***	18.131***	16.267***
	(11.712)	(8.184)	(6.771)	(7.457)	(8.068)	(8.364)	(8.236)	(6.747)	(5.290)
GDP2	−1.404**	−1.325***	−1.436***	−1.511***	−1.445***	−1.187***	−0.960***	−0.858***	−0.771***
	(0.549)	(0.834)	(0.318)	(0.351)	(0.381)	(0.395)	(0.389)	(0.319)	(0.250)
TO	0.047***	0.154***	0.151***	0.142***	0.137***	0.175***	0.210***	0.258***	0.302***
	(0.857)	(0.041)	(0.033)	(0.038)	(0.037)	(0.038)	(0.037)	(0.036)	(0.031)
URB	−1.818***	−1.839	−1.653***	−1.655***	−1.651***	−1.651***	−1.649***	−1.746***	1.732***
	(0.303)	(0.222)	(0.176)	(0.187)	(0.175)	(0.159)	(0.154)	(0.143)	(0.169)
Obs.	175	175	175	175	175	175	175	175	175

Note: *** and ** denote the 1 % and 5 % significance levels, respectively. Values enclosed in parentheses denote standard errors.

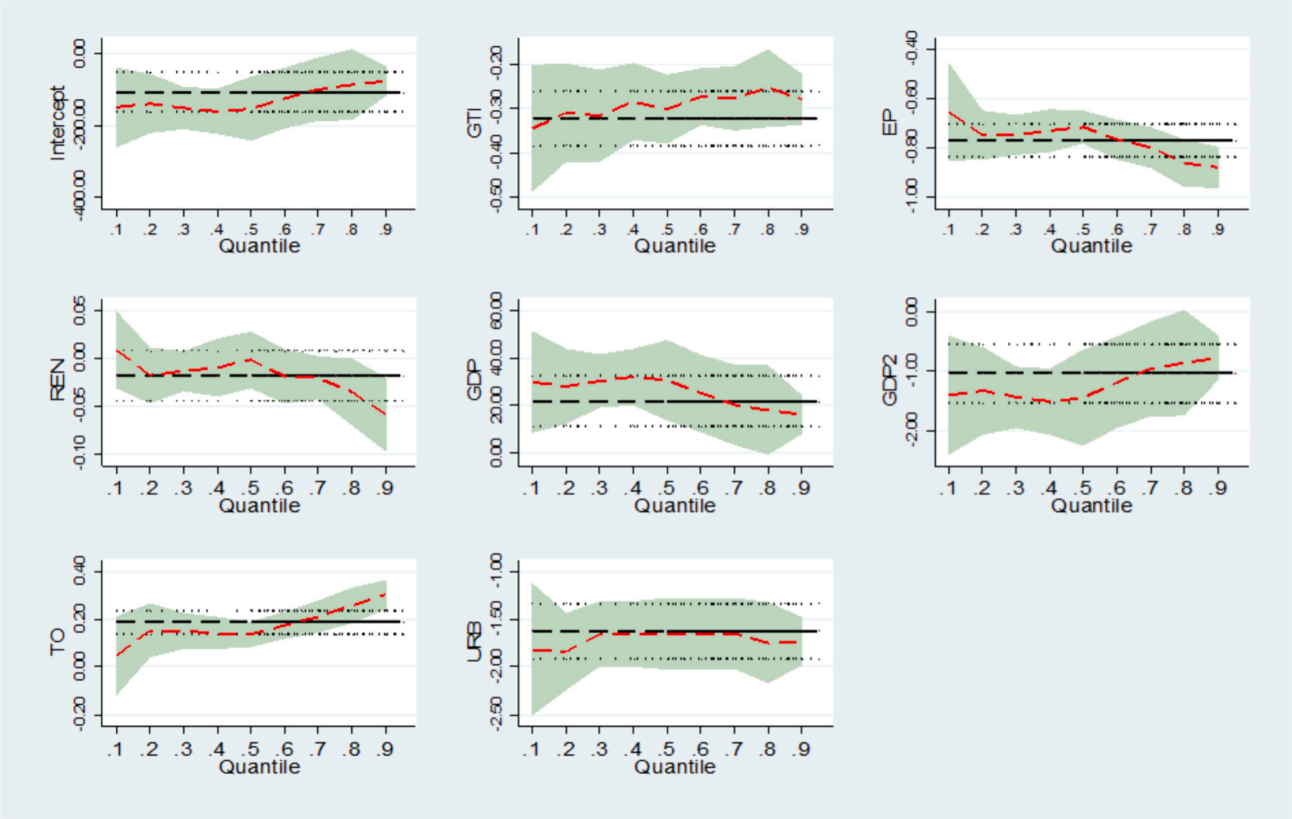

Fig. 9. PQR estimates. Note: The shaded area represents the 95 % confidence interval.

The findings observed that GDP significantly and positively affects the level of EFP at all quantiles, demonstrating that a rise in economic activity degrades the environmental quality. However, the magnitude of the impact is heterogeneous at all quantiles (see Fig. 9). Further, we discovered a significant negative influence of GDP^2 on the level of EFP at all quantiles. This negative relationship points out that GDP^2 is important in reducing environmental deterioration. Thus, GDP^2 enhances ecological sustainability. However, this effect varies at all quantiles, with a significant impact observed at the lower to middle quantiles. This result confirms that the EKC hypothesis holds at all quantiles (10th to 90th). As expected, the study observed a significant positive interconnection between TO and EFP at all quantiles (0.10 to 0.90), which implies that trade activities enhance environmental degradation by increasing EFP and consequently deteriorate ecological sustainability. Nevertheless, the size of the impact of TO enlarges as we shift from lower to the middle to the upper quantiles. After that, urbanization revealed a favourable and statistically significant effect on the EFP at all levels. It implies that urbanization reduces the EFP and boosts ecological sustainability. Table 10 and Fig. 10 present the summary of PQR estimates for all the research variables.

Table 10
Summary of PQR outcomes.

Variables	Lower quantile ($\tau =$ from 0.10 to 0.30)	Middle quantile ($\tau =$ from 0.40 to 0.60)	Upper quantile ($\tau =$ from 0.70 to 0.90)
GTI	−	−	−
EP	−	−	−
REN	−	−	−
GDP	+	+	+
GDP^2	−	−	−
TO	+	+	+
URB	−	−	−

Note: − and + signs indicate significant negative and positive connections between dependent and independent variables.

4.2. *Discussion of results*

This section discusses the outcomes regarding the association between the explained (EFP) and explanatory variables (GTI, EP, REN, GDP, GDP^2, TO, and URB). Concerning the impact of GTI, the estimated outcomes have revealed that GTI is negatively linked to the EFP and enhances ecological sustainability in all the regression models. GTI reduces the level of EFP and enhances ecological sustainability since the advancement of GTI encourages the usage of clean energy, smart machinery, and other applications and, as an outcome, enhances energy efficiency, reduces the utilization of natural resources, and produces less waste and ecological damage caused by humans during the production and consumption processes. The conclusion of our study is coherent with those of Ahmad and Wu (2022), who discovered a beneficial impact of GTI on the EFP. Javed et al. (2023a) also revealed a constructive impact of GTI on the environmental health in Italy. Similarly, Zeraibi et al. (2021) also confirmed the ecological deprivation reduction impact of GTI in the case of five ASEAN countries. Many other studies also endorsed these results, such as Shan et al. (2021) in Turkey, Liao et al. (2023) in OECD countries, and Koseoglu et al. (2022) in 20 top green innovator nations. Overall, the development and adoption of GTI significantly reduces environmental deterioration and maintains the ecological balance. To this end, government institutions, the private sector, businesses, and academic institutions must increase their R&D expenditures to fund the development of GTI. Further, governments should adopt policies that promote both the creation and widespread implementation of such technologies.

Next, all the regression outcomes reveal a negative influence of environmental policy on the level of EFP, suggesting that EP enhances ecological sustainability in the examined countries. The execution of EP

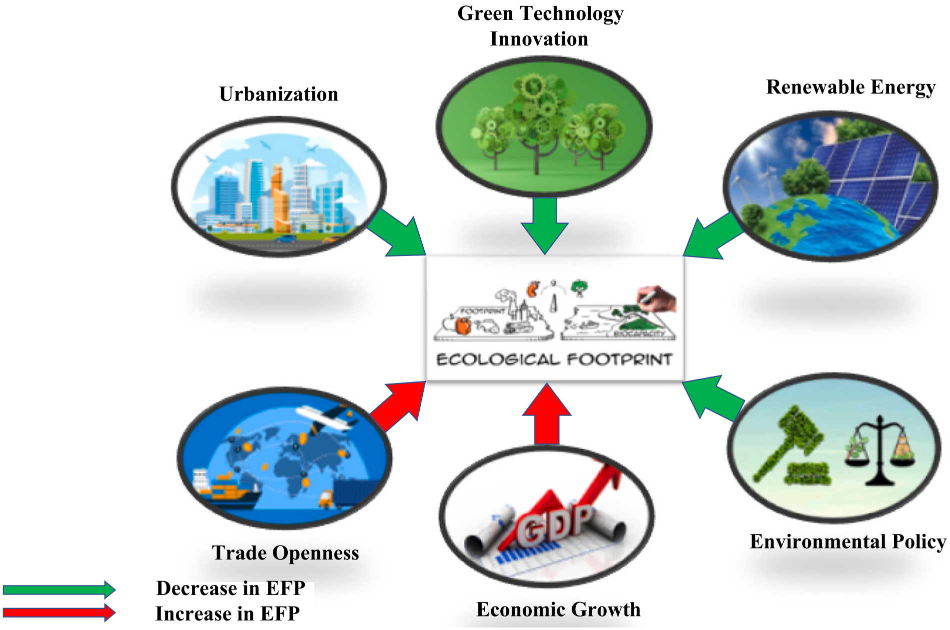

Fig. 10. Summary of the FMOLS, DOLS, FE-OLS, and PQR estimates.

pushes the business to adopt eco-friendly technology and use green energy in their manufacturing process, resulting in more efficient usage of resources and energy with less environmental degradation (Javed et al., 2023a). It is also believed that environmental taxes influence consumers' decisions to adopt more cost-effective and environmentally friendly consumption practices. These outcomes coincide with the results (Rafique et al., 2022; Nathaniel and Adedoyin, 2020; Fang et al., 2023; Ullah et al., 2023; Chu and Tran, 2022; Doğan et al., 2022). They all argued for the constructive effect of EP on environmental quality.

Further, we observed a negative linkage between REN and the EFP in all the regression estimates. This suggests that the shift from fossil fuels to clean energy enhances ecological sustainability. Javed et al. (2023a) suggested that using REN helps countries achieve environmental goals and boost ecological sustainability without slowing economic development. Furthermore, switching to renewable energy sources can reduce energy costs, improve air quality and human health, generate new employment opportunities, and lessen the negative effects on the climate. The outcomes of our study are in harmony with those of Danish et al. (2019) for BRICS, Usman and Hammar (2021) for APEC, Zhang et al. (2022b) in the case of E-5, Destek and Sinha (2020) for 24 OECD countries, Sahoo and Sethi (2021) for developing countries, and countries. They all argued that the usage of clean energy betters environmental health. Because of this, it is believed that including more forms of green energy in the total final energy consumption is the best way to promote green growth without harming the environmental quality or the availability of natural resources.

Next, the results demonstrate a favourable GDP-EFP relationship for all the estimated approaches, signifying that increased economic activity boosts environmental degradation. Conversely, the square term of GDP negatively influences the EFP. These results provide evidence of the inverted U-shaped relationship and the validity of the EKC hypothesis in all the estimated models. The EKC theory explains that in the early stages of economic development, the scale effect intensifies the environmental degradation through excessive utilization of resources and energy; however, after reaching a threshold level of growth, a further upsurge in economic development reduces the environmental deprivation through smarter infrastructure, environmentally friendly policies, and creative solutions. The occurrence of the EKC theory in G-7 countries postulates that these nations have accomplished a certain stage of economic development and are now progressing towards green growth with the help of GTI, environmentally friendly policies, and clean energy sources in the production process, which helps curb environmental deterioration. This finding is consistent with (Javed and Rapposelli, 2022; Anwar et al., 2021; Miao et al., 2022; Mahmood, 2023). The above-mentioned studies confirmed the existence of EKC hypotheses.

Further, all the estimated models illustrate that TO harms EFP, implying that trade activities enhance environmental degradation. This is justified by the statistic that the G-7 countries are the world's major industrialized countries and persistently maintain their economic development by rapidly expanding trade activities and the manufacturing sector. Thus, a rise in manufacturing and trade activities necessitates more use of resources and energy, and as a result, an upsurge in energy utilization, land, water, and other resources produces more industrial waste. Consequently, intensifying trade activities negatively affects the environment and reduces ecological sustainability. Our results are consistent with earlier studies. For instance, Al-Mulali et al. (2016) revealed the positive impact of TO on the EFP in the context of 58 countries. Similarly, Ozturk et al. (2016) showed that trade activities degrade the environment in 144 countries. Abid et al. (2022) indicated that TO is the key factor of environmental deprivation in Saudi Arabia. Sabir and Gorus (2019) also discovered that TO degrades the environmental health in South Asian nations.

In the case of urbanization, findings revealed an environmental reduction in all the estimated models. This illustrates that URB improves ecological sustainability by reducing the level of EFP in underlying countries. The positive environmental impacts of URB that counteract the negative effects could result from several factors. For instance, the increased disposable income that comes with URB benefits the environmentally friendly services sector and increases the demand for environmental quality, both of which have a decreasing impact on EFP. Second, compared to rural areas, metropolitan areas have higher living standards and greater amenities, contributing to lower EFP. Third, urbanization encourages R&D and innovation, lowering environmental degradation (Charfeddine, 2017). Compared to the global average of 54.1 %, the G-7 countries' urbanization rates are significantly higher, at 75.59 %. The urban population of these nations is thought to have sufficient income to partake in environmentally friendly activities like the use of renewable energy sources, electric cars, buses, and other appliances that are energy efficient and produce less waste. This enhances the efficiency of resource utilization and, as a result, lowers the EFP (Javed

Table 11
Slope equality Wald test outcomes.

Variables	0.10 vs 0.20	0.10 vs 0.50	0.10 vs 0.70	0.10 vs 0.90
GTI	−0.035**	0.017	0.004**	0.025**
EP	0.097*	−0.015***	0.031	0.017
REN	0.027**	−0.008*	0.001*	0.023
GDP	1.855***	1.244*	4.719*	1.899*
GDP^2	−0.079*	−0.061	−0.222*	−0.088
TO	−0.107*	0.005*	−0.035	−0.044**
URB	0.022**	−0.003	−0.006*	−0.013

Note: ***, **, and * denote the significance level at 1 %, 5 %, and 10 %. H0 indicates that the slope coefficients are equal.

et al., 2023a; Danish and Wang, 2019). The results of the present study are in harmony with earlier studies (Nathaniel et al., 2019; Hassan et al., 2019; Yasin et al., 2020; Zhou et al., 2022). Next, Table 11 displays the outcomes of the Wald test for determining if two slopes are identical. The null hypothesis of slope equality has been rejected for most of the quantile comparisons. This result is in line with our panel quantile regression results, which indicate that the effects of GTI, EP, REN, GDP, GDP^2, TO, and URB on ecological sustainability are shown to vary considerably across quantiles. The study is conducted in a highly developed economic context of G-7, and the results of the study are generalizable to countries sharing similar economic, technological, social, and political structures.

In the final step, we observe and verify the causal association among the explained (EFP) and the explanatory variables. Despite providing reliable estimates, FMOLS, DOLS, FE-OLS, and PQR approaches lack the mechanisms for accessing the causal connection and overlook the causality direction between the underlying variables. For this, the present research used Dumitrescu and Hurlin's (2012) panel granger causality, and the outcomes are reported in Table 12. The Wald statistics and *Z*-score are used to test the null of no causal association. The study results indicate that the Wald statistics and Z-score have statistically significant values for most causal relationships. The hypothesis that there is no connection among the variables under consideration is thus rejected. Instead, the findings demonstrate a unidirectional and bidirectional connection between the examined variables. The statistics specify a unidirectional relationship between the GTI and EFP, the EP and EFP, the TO and EFP, and the URB and EFP. However, the outcomes also validate a bi-directional causality between GDP and the EFP, GDP^2 and the EFP, REN, and the EFP. The causality relation between the research factors demonstrates that any policy change for GTI, EP, REN, GDP, TO, and URB will have a substantial influence on the EFP in G-7 countries. Fig. 11 shows the direction of causality between the variables.

Table 12
Granger causality outcomes.

Null hypothesis	Wald statistic	Z-value	P-value
GTI $\neq$ EFP	7.316***	5.254	0.000
EFP $\neq$ GTI	3.490	1.264	0.198
EP $\neq$ EFP	11.451***	9.542	0.000
EFP $\neq$ EP	3.275	1.063	0.288
REN $\neq$ EFP	9.929***	7.964	0.000
EFP $\neq$ REN	4.889***	2.737	0.006
GDP $\neq$ EFP	7.585***	5.324	0.000
EFP $\neq$ GDP`	4.467***	2.299	0.004
GDP^2 $\neq$ EFP	7.591***	5.539	0.000
EFP $\neq$ GDP^2	4.469***	2.301	0.021
TO $\neq$ EFP	15.928***	14.185	0.000
EFP $\neq$ TO	2.366	0.119	0.904
URB $\neq$ EFP	5.968***	3.856	0.000
EFP $\neq$ URB	3.328	1.118	0.263

Note: *** indicates significance level at 1 % level.

5. Conclusion and policy recommendations

The present research empirically examines the role of GTI, EP, REN, GDP, GDP^2, TO, and URB on ecological sustainability in G-7 economies from 1994 to 2018. Before conducting the empirical estimation, this research employs a battery of preliminary tests to learn about the characteristics of the panel data. We used the parameters SCH test by Pesaran and Yamagata (2008), the CSD test developed by Pesaran (2007), and the 2nd-generation stationarity test by Pesaran (2007), respectively, to validate the occurrence of a heterogeneous slope model, cross-sectional dependency, and variables integration order. Further, we employed the Westerlund (2007) cointegration test to investigate the long-term cointegration between the dependent (EFP) and explanatory variables. Based on the findings of these preliminary tests, we constructed the most appropriate econometric model to investigate the relationship between the research factors empirically. For this purpose, this study employs the Panel Quantile Regression (PQR) alongside several long-run mean estimation methods (FMOLS, DOLS, and FE-OLS) for robustness. Compared to the traditional long-run mean estimation methods, the PQR approach gauges the heterogeneous effects between the EFP and its determining factors. Finally, we utilized the causality test by Dumitrescu and Hurlin (2012) to examine the causal linkages between the variables under consideration. The slope heterogeneity test indicates that the study model has a slope heterogeneity issue. The CSD test outcomes confirm the cross-sectional dependency in the dataset. Further, the stationarity test demonstrates the mixed integration order of variables. The Westerlund (2007) test provides evidence of long-run cointegration association between the variables. The findings of mean estimates (FMOLS, DOLS, and FE-OLS) explain that increases in GTI, EP, and REN enhance ecological sustainability by lowering the EFP. Moreover, a rise in GDP increases the EFP and enhances environmental degradation, while GDP^2 reduces the EFP. The negative significant values of GDP^2 in all the methods support the EKC hypothesis. Further, results indicate that TO harms the environment by increasing the EFP. On the other hand, URB reduces the EFP in all three estimates. The results of PQR reveal that GTI and EP have a significant beneficial impact on the EFP at all quantiles, suggesting that GTI and EP enhance ecological sustainability at all quantiles. Moreover, REN also shows an ecological protection effect at the 20th to 90th quantile. The outcomes illustrate a significant positive influence of GDP on EFP at all quantiles. On the flip side, GDP^2 had a negative effect on the EFP across all the quantiles. These findings also prove the validity of the EKC hypothesis. Further, results explain that TO significantly positively affects the EFP and enhances environmental degradation in all quantiles. Contrary to this, urbanization has an adverse relation with EFP at all quantiles. Finally, granger causality results provide evidence of unidirectional causality from GTI, EP, TO, and URB with EFP and a bidirectional causality running from REN, GDP, and GDP^2 to EFP.

Based on the outcomes, the present study proposes valuable policy suggestions to fight against environmental degradation and achieve ecological sustainability. The results show that the advancement of GTI and the transition from fossil fuel energy to clean energy sources negatively affect environmental degradation and enhance ecological sustainability. The G-7 countries should provide substantial funding for green technology innovation-related R&D activities. Further, the government should enact policies that provide subsidies and tax exemptions to firms working on the development of GTI. Additionally, environmental policy's significant negative impact on EFP helps promote ecological sustainability; thus, the G-7 economies should strengthen these environmental policies to achieve ecological sustainability targets. The government's ability to fight against the pollution caused by industries and fossil fuel energy sources can be improved through strict environmental policies. Governments should enact several environmental regulatory mechanisms like permits, taxes, and fines on pollution to promote green growth and endorse policies that incentivize businesses to adopt environmentally friendly processes and products by

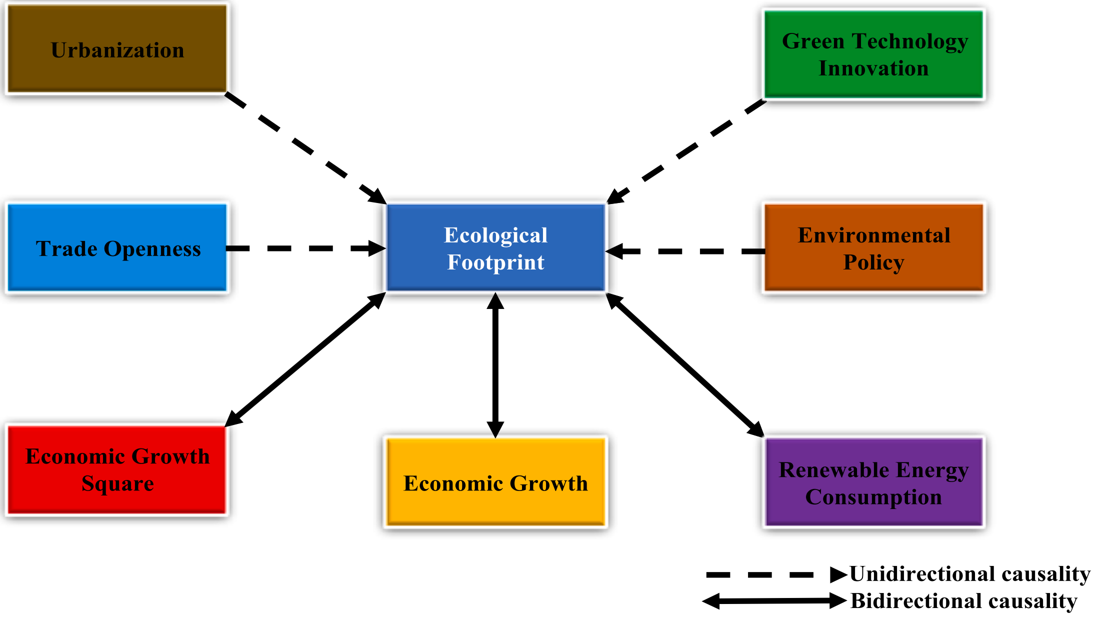

Fig. 11. Causal links of independent variables with ecological footprint.

providing subsidies or other financial support. By investing in improving clean energy technologies and implementing strict environmental policies, the G-7 nations can alleviate the adverse environmental impacts of trade activities and economic development.

This study evaluated the role of GTI, EP, and REN, along with important control variables, in ecological sustainability in a group of G-7 countries. However, the present research has some shortcomings. The limitations of the present study necessitate further investigation by researchers in the future. This study advises that future studies should consider additional prospective determinants alongside the already mentioned variables, such as green growth, green investment, green finance, and green trade, which are all considered growing areas for creative policy instruments related to ecological sustainability. Further, the present study used the panel quantile regression technique, which provides heterogeneous estimates; however, it does not offer any short-run estimates. Therefore, this study suggests using advanced econometric techniques like CS-ARDL and PMG-ARDL, which provide long- and short-run estimates. Moreover, this research only considers the G-7 countries for analysis. However, this research can be extended to other blocks such as the BRICS, MENA, OECD, EU, E-7, and G-20 countries. Lastly, researchers can conduct comparative studies between the developed and developing economies.

CRediT authorship contribution statement

Aamir Javed: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Agnese Rapposelli:** Project administration, Supervision, Validation. **Feroz Khan:** Writing – original draft, Writing – review & editing. **Asif Javed:** Data curation, Writing – original draft, Writing – review & editing. **Nabila Abid:** Validation, Visualization, Writing – review & editing.

Data availability

Data will be made available on request.

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Aamir Javed is a Research Fellow at the Department of Economics Studies, "G.d' Annunzio" University of Chieti-Pescara, Italy. He completed his PhD at Department of Management and Business Administration, "G.d' Annunzio" University of Chieti-Pescara, Italy. During his PhD, he was a visiting scholar at the Centre for Business and Economics Research-CeBER, Faculty of Economics, University of Coimbra, Portugal, and Faculty of Economics, Marmara University, Istanbul, Turkey. His research interests focus on applied economics, energy and environmental economics, green technological innovation, international finance, and efficiency evaluation methods. He has published quality publications in journals of international repute

Agnese Rapposelli is Senior Assistant Professor of Economic Statistics at the Department of Economics Studies, "G.d' Annunzio" University of Chieti-Pescara, Italy. She was a visiting scholar at Warwick Business School (UK), where she worked under Prof. R.J. Dyson's supervision (Operational Research & Systems Group). Her research interests focus on efficiency evaluation methods, with a special focus on Data Envelopment Analysis and Stochastic Frontier Analysis. During the past 20 years, she has conducted research in the following areas: urban waste services, the airline industry, corporate governance and firm performance, environmental efficiency, and sustainable development. Besides, she has conducted major studies on the inclusion of people with disabilities in the Italian labor market. She is the author/co-author of a book and over 50 papers published in international leading journals or refereed edited volumes.

Feroz Khan is currently doing his Ph.D. in Accounting Management and Business Economics at the Department of Management and Business Administration, "G.d' Annunzio" University of Chieti-Pescara, Italy. His research interests include Operations Management, Supply Chain Management, Sustainability, and Energy Economics. He has published quality publications in journals of international repute.

Asif Javed is a Ph.D student of Science and Technology for Sustainable Development at the Department of Advanced Technologies in Medicine & Dentistry Center for Advanced Studies and Technology-CAST), "G.d' Annunzio" University of Chieti-Pescara, Italy. His research interests focus on the labor market, energy transition, green hydrogen, environmental policies, and international trade.

Nabila Abid is an Assistant Professor in the Department of Strategy and Entrepreneurship at EM Normandie Business School, France. She completed her PhD at Department of Management and Business Administration, "G.d' Annunzio" University of Chieti-Pescara, Italy. During her doctoral studies, she was a visiting PhD scholar at Regensburg University, the Technical University of Munich in Germany, and Newcastle University Business School in the UK. She has also worked as a Lecturer at Northumbria University, Amsterdam campus. She has published articles in reputable journals. Her primary research focuses on entrepreneurship, environmental sustainability, green innovation, sustainable performance, and green transition in both developing and developed countries.