



Role of environmentally related technologies and revenue taxes in environmental degradation in OECD countries

Nudrat Fatima¹ · Zheng Yanting¹ · Ni Guohua¹

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Abstract

The purpose of this study is to validate the impact of foreign direct investment inflows (FDI inflows), trade openness (TO), environmentally related technologies (ERTs), environmentally related tax revenues (ERTRs), and economic growth (EG) on carbon dioxide (CO₂) emissions by employing a PMG (pooled mean group) estimator with a dataset of 36 OECD countries spanning from 1990 to 2020. Im-Pesaran-Shin, Fisher-type, and cross-sectional augmented Dicky-Fuller tests indicate that study variables are stationary at I (0) and I (1). Kao and Pedroni cointegration test results show that cointegration exists across regressors and regressands throughout the sample of OECD countries. The results of the Hausman test confirm that the PMG panel ARDL method can be employed. Empirical results of PMG demonstrate that ETRs help to reduce CO₂ emissions, while FDI inflows, TO, ERTs, and EG are significant and positively related to environmental degradation. This study is an effort to fill the gap by exploring the role of ERTs and ETRs in environmental degradation in selected OECD countries. The study findings support the relationship between CO₂ emissions, ERTs, and ETRs. It has been determined that environmental technologies and revenue taxes are also drivers of environmental sustainability. The study provides policymakers with pertinent implications for promoting the development and adoption of green technologies. The findings suggest that imposing environmental taxes expedites the development of environmentally related technologies for reducing CO₂ emissions and promoting sustainable development in OECD countries, with potential applications in a wide range of countries, particularly as a basis for emerging countries to boost their energy transition timelines.

Keywords Foreign direct inflows · Trade openness · Related environmental technologies · Environmentally related tax revenues · Economic growth · Pooled mean group estimator · Quantile regression

Introduction

International sustainable development strategies have been implemented in response to mounting environmental concerns. The impact of rising temperatures around the globe on living things has been increasing for the past 150 years (Sun et al. 2020). Since 1980, an enormous 80% rise from 19 to 36 million metric tonnes of CO₂ has been released into the atmosphere

(Taghizadeh-Hesary and Taghizadeh-Hesary 2020). According to the IEA report, worldwide energy consumption is expected to increase by 28% by 2035. This might have a negative impact on the natural world. Several issues have been brought to light, including the need for environmental justice to prevent significant harm to the Brazilian Amazon jungles, which produce 20% of the world's oxygen and have increased water demand due to harsh temperatures and severe drought (Mohsin et al. 2018a, b; Ikram et al. 2019). Fires in the Amazon rose by 83% this year, posing a threat to the homes of countless animal species and ancient civilizations (Pham et al. 2021).

Energy consumption also rises as a result of industrialization and, by extension, globalization. The trade-off between EG and environmental quality results in a massive rise in energy consumption, which is difficult to control. The reliance on fossil fuels to supply energy needs compounds the challenge of finding a solution. The association between environmental quality and EG has been the subject

Responsible Editor: Eyup Dogan

✉ Zheng Yanting
zhengyanting@th.btbu.edu.cn

Nudrat Fatima
nudratfatima91@gmail.com

Ni Guohua
niguohua@btbu.edu.cn

¹ Beijing Technology & Business University, Beijing, China

of many recent studies in the energy-environment literature (Apergis and Payne 2010; Alola et al. 2019; Zafar et al. 2019; Ali et al. 2020). There have been several descriptions and analyses of the association between EG and the natural environment throughout the past decade. One popular scientific framework for examining the association between economic growth and environmental deterioration is the environmental Kuznets curve (EKC Hypothesis). An inverted U-shaped association is postulated between EG and CO₂ emissions, with the theory stating that CO₂ increases as per capita income rises during the early stages of EG. If this correlation holds, EG has the potential to be a powerful instrument for helping developing nations improve environmental quality and eventually develop economically enough to solve their ecological concerns. This claim highlights the importance of investigating the theory's generalizability, especially in light of the possibility of a different connection between economic development and environmental deterioration in less developed nations.

Many environmental elements have been connected by researchers during the past decade (Wang et al. 2021; Awosusi et al. 2021; Murshed et al. 2021; Wu et al. 2021). With longitudinal data from the World Resources Institute for industrialized nations, Selden and Song (1994) calculated environmental Kuznets curves for four emission series: SO₂, NOX, SPM, and CO₂ (WRI). From what they were able to gather from their research, they deduced that the magnitude of the emission change was likely to be larger than background levels. They explained how a smaller number of cities experience higher core population density increases in the initial stages of EG, but this trend reverses itself in the later stages of development. The fate of each nation is determined by its economy (Nawaz et al. 2019). The economy of a country may be boosted by several things, including tax income, exports, imports, trade, environmentally related technologies (ERTs), foreign direct investment, etc. Whether the economy is trending upward or downward depends on how these factors are combined. Foreign direct investment (FDI) is a growth-promoting factor for every economy. FDI is described as capital flowing from one country to another. Lower production costs, higher-quality products, and shorter lead times all attract investors from one nation to another. One of the main motivations for FDI in any country is economies of scale, which lead to lower manufacturing costs, as explained by internationalization theory (Siddique et al. 2017).

Trade openness (TO) is a major factor that boosts the world economy's performance, but it also causes major environmental degradation problems, such as excessive CO₂ emission. It was discovered by Prasad and Asafu-Adjaye (2003) that a positive correlation between TO and environmental deterioration requires a particular and suitable agreement between trade nations. As the effects of climate change and global warming become more apparent, a comprehensive strategy is needed to address them. Environmental taxes

are quickly becoming the basis for a sustainable environment and a remedy for reducing CO₂ emissions in light of these serious concerns and the realization that market mechanisms alone cannot fix environmental challenges (Pigou 1920).

Greenhouse gas (GHG) emission taxation is one of the most effective emission reduction techniques (Santos et al. 2018). Both Stevens (2021) and González-Estrada and Camacho-Amador (2018) found that carbon pricing systems put a price on carbon products and taxed them. In the end, these measures will lead to a world without carbon emissions by encouraging corporations to invest in environmentally friendly technology development. For EG and a sustainable future, green growth is a crucial factor in enhancing economic activity (Danish and Khan 2020). The term "green growth" refers to an economic expansion that emphasizes environmentally responsible manufacturing and consumption practices. Mensah et al. (2019a, b) state that the usage of ERT in manufacturing contributes to a lower rate of environmental deterioration. The impact of ERT on environmental quality has been studied and found to differ among nations. In addition, a comprehensive set of environmental policies and an understanding of market externalities are necessary to make the transition to ERT a success. Efficient technological advancements are critical to cutting down on carbon dioxide emissions (Khan et al. 2020b). Since governments are enacting laws and plans to better the environment, green technology plays a significant role in emission reduction. Many experts in the field blame progress in technology for warming the planet and increasing carbon dioxide emissions. Thus, governments are actively promoting and subsidizing investments in relevant environmental technology. As a result of these considerations, the main objective of this study is to use the most recent PMG panel ARDL approach to assess the effect of EG, environmental technology, FDI inflows, TO, and environmental tax revenues on CO₂ emissions.

The main responsibility of governments is to foster economic growth. It is the prime means by which many underdeveloped nations may escape from abject poverty. However, more natural resources need to be exploited if expansion is to be accelerated. While the world's economy greatly benefited from the industrial revolution, the environment suffered unprecedented damage. The environment is deteriorating due to several factors, including increased pollution in rivers, decreased animal habitat, degraded soil quality, global warming, and ozone depletion. Efficient utilization of resources is achieved by the application of EG and improved technological capacity. However, many natural ecosystems are essential to human life and cannot be replaced. These include air and soil quality, control of climate change, nutrient cycling, waste disposal, and disturbance regulation. As a result, resource efficiency is crucial for maintaining EG over time. Therefore, environmental policymakers need to know

how environmentally related technologies and revenue taxes affect the environment and how to anticipate changes in that relationship (Shabbir et al. 2019; Shabbir et al. 2020a, b).

Most OECD countries are highly industrialized, densely populated nations that participate in international trade and expand beyond their borders. The OECD countries obtain their energy from a variety of sources, creating multifaceted CO₂ emission sources. The data in the “Recent Trends in the OECD: Energy and CO₂ Emissions” report of 2016 demonstrate that oil contributes to the largest share of 40% in CO₂ emissions, followed by coal at 33% and gas at 26% across the OECD countries (Mensah et al. 2018). Therefore, it is a matter of concern for OECD countries to promote innovation in all fields related to CO₂ emissions in order to contribute to the reduction of CO₂ emissions. Therefore, the main purpose of this study is to assess the significance of ERTs and environmentally related tax revenues (ERTRs) on carbon dioxide (CO₂) emission using panel data econometric techniques, namely cross-sectional dependency and pooled mean group ARDL. To achieve this objective, the current study focused on a dataset of 36 OECD countries.

The variables of interest, i.e., ERTs, are measured by patents with fractional country values, while ERTRs are measured by tax revenues as a percentage of GDP. In continuation of the previous debate, this study has the potential to add to the existing literature and pave the way for similar investigations in other countries. The following empirical gaps are found after reviewing a summary of the extant literature: (i) The effects of technological innovation and energy consumption on ecological footprint have been the subject of many studies, but the combined (interaction) effects of EG, FDI inflows, TO, environmentally friendly technologies, and ERTRs on CO₂ emissions have received less attention. (ii) Using panel data from 1990 to 2020 for 36 OECD countries and the Pooled Mean Group ARDL technique to investigate the impact of environmental degradation on CO₂ emissions, this research intends to fill these gaps in the literature. Thus, the study findings expand the horizons previously explored in the literature around the EKC theory.

In the “Introduction” section, we looked at the background of variables of interest and the importance of OECD countries in the global climate change negotiation platform and counter-action policies. The following section examines the literature on the subject of this paper. This study develops analytical arguments in line with the objective of the study by reviewing the existing literature. The third section of the paper dealt with methodological concerns. This section also includes a description of data sources. The fourth section of the paper is about the results and discussion determined using a panel data analysis. The fifth section of the paper includes the conclusion and policy recommendations.

Literature review

In the last few decades, climate change, global warming, and the general deterioration of environmental quality have emerged as pressing problems on a worldwide scale. New technologies have increased the need for energy in both developing and industrialized nations. While energy consumption is a factor in EG (Saidi and Mbarek 2016), it is also a major contributor to environmental degradation. The rise in global CO₂ emissions has made environmental deterioration an urgent problem (Dogan 2016). Therefore, to attain CO₂ neutrality, it is important to investigate the numerous energy drivers that affect variations in CO₂ emissions (Chen et al. 2018). Numerous empirical studies have been done throughout the years to examine the causes of environmental degradation. Conflicting conclusions have been drawn from such studies, however, due to differences in the proxies employed. Thus, the current study used several proxies like TO, EG, FDI inflows, ERTs, ERTRs, and CO₂ emissions to offer the globe a thorough grasp of environmental degradation components. The following section provides a summary of studies that examine the impact of TO, EG, FDI inflows, ERTs, and ERTRs on CO₂ emissions.

Nexus between FDI inflows and CO₂ emission

Both policymakers and academics have recently placed a greater emphasis on the link between environmental sustainability, TO, ERTs, ERTRs, FDI inflows, and EG. Many studies have investigated the factors that influence environmental outcomes, including foreign direct investment, trade, and economic development. The findings from research into the factors that shape our environment, on both a large and small scale, are contradictory. Studies have shown that better resource allocation at home can lead to a longer life span and better quality of life when trade and FDI are both encouraged. Although such pursuits increase technological innovation and decrease pollution, according to certain research, Rasoulinezhad and Saboori (2018) observed a favorable nexus between CO₂ and economic growth in Myanmar. According to the research conducted by Saud et al. (2019), economic growth, FDI, and TO all improve environmental quality in BRI nations, whereas GDP has a negative impact. Rasoulinezhad and Saboori’s (2018) research found a link between these four factors and CO₂ emissions. CO₂ emissions are influenced by TO and EG, according to research by Cetin et al. (2018). Research pointing in this direction has found that more investment and trade lead to more advanced technology, which in turn leads to less pollution from factories. In

addition, the positive environmental impact is reinforced when advanced environmental standards are imparted to emerging economies through economic and technological exchanges.

Nexus between environmental degradation and TO

Because TO is highly correlated with money and economic growth, it has a wide range of environmental consequences, including scale effects, composition effects, and technology effects. Water shortages, sanitation, and urban waste appear to be unaffected by any of the trade policy factors examined by Shafik and Bandyopadhyay (1992), but reduced reliance on forest resources and lower levels of sulfur dioxide and CO₂ emissions are characteristic of more open economies. The increasing trade-induced CO₂ emissions in 26 industries in newly industrialized nations (manufacturing, agriculture, mining, and services) may be slowed by adjusting the input mix, fuel mix, sector energy intensity, and carbon intensity of fuels. Using the autoregressive distributed lag (ARDL) approach, Jalil and Mahmud (2009) demonstrated that TO and CO₂ emissions have a positive and statistically significant association. The findings of Yang et al. (2022) suggest that commercialization and urbanization may have a more long-term negative impact on environmental quality than their short-term positive effects. Concern about the environment's deterioration has made environmental protection a hot topic across the world in recent decades. From this vantage point, the environmental impact of trade is becoming an increasingly important topic of discussion in the realm of trade policy. Many recent studies have used empirical methods to investigate the link between TO and ecological health (Shahbaz et al. 2013; Amin et al. 2020). The results of this study show conflicting results, with some findings suggesting a positive correlation and others a negative one. The available literature implies that commerce helps economies expand. As an example, China's extraordinary growth has been fuelled in large part by the country's adoption of the international commercial system. If more commerce leads to increased economic activity, and increased economic activity leads to increased environmental degradation, then economies experiencing this problem must adopt more stringent environmental restrictions. The quality of the environment will likely improve as we adopt more eco-friendly industrial methods. Sulfur dioxide emissions were used as a proxy for pollution levels, and the authors of Jun et al. (2020) found that economies with more open economies had lower levels of pollution. Baek et al. (2009) found that in both developed countries and China, increased trade and affluence significantly improved environmental quality. Evidence of a negative long-term link between commerce and oil-related CO₂ emissions across nations

with differing economic levels was found by Boulatoft and Jenkins (2010).

Environmental degradation and ERTs

Numerous analyses have been performed to determine ERTs' value in sustainable development. The connection between sustainable development and technological progress was studied by Mensah et al. (2019a, b). MLR, IPAT, and STIRPAT methods were used on data gathered from 28 nations. Their research shows that while every country has its own unique set of needs, innovative technology use is essential for sustainable development. Azevedo et al. (2018) did a similar analysis of the BRICS nations' CO₂ emissions between 1980 and 2011. They concluded that economic activity has a significant influence on the environment; however, this effect differs from nation to nation. Gu et al. (2019), Liu et al. (2022), and Tian et al. (2021) demonstrated that energy resources might significantly cut down on carbon dioxide emissions and thus boost environmental quality. ERTs can increase efficiency (Zhang et al. 2021a, b), reduce costs (Koçak and Ulucak 2019), make energy more accessible, and increase EG penetration (Ockwell et al. 2010; Liu et al. 2008; Li et al. 2022). Different statistical techniques were used on various environmental factors in several studies done throughout time to investigate the impact of energy-related technologies, inventions, R&D expenditures, and investments on carbon dioxide emissions. With the EKC paradigm, Hussain and Dogan (2021), Lin et al. (2022), Qiao et al. (2022), and Wang et al. (2022a, b) analyzed the correlation between ERT, institutional quality, and energy consumption in the BRICS nations from 1992 to 2016. They factored in GDP and GDP square and found that ERT and institutional quality had a favorable impact on the natural world. Environmental quality in the G-7 countries varied between 1990 and 2018, as demonstrated by Ding et al. (2021) and Wang et al. (2022a, b) using a battery of statistical tests. Evidence from these researchers shows that certain characteristics are robust predictors of consumption-based CO₂ emissions in the sample nations.

Nexus between environmental degradation and ERTs

Environmental policy and environmental protection are two major policy instruments for addressing CO₂ emissions (Haites 2018; Tao et al. 2021; Wolde-Rufael and Mulat-weldemeskel 2022). The point of an environmental tax is not simply to make money for the government; it is also to encourage companies to adopt more environmentally friendly practices and encourage individuals to reduce their environmental impact by shifting to less damaging consumption habits (Pigou 1920; Ghazouani et al. 2020; Esen et al. 2021). A carbon price has the potential

to reshape the economy in a way that reduces the environmental impact of production and consumption (Zhang and Zhang 2018; Shahzad 2020). Carbon dioxide (CO₂) emissions can be reduced, green technology can be advanced, and energy consumption can be optimized thanks to environmental levies (Bashir et al. 2022). According to research by Kiula et al. (2014), environmental taxes are preferable for protecting the environment since they spur economic growth, reduce labor taxes, and reduce unemployment (Shahzad 2020). The “double dividend” idea (Pearce 1991) states that the environmental tax should have dual goals: (I) to increase environmental quality (the “green dividend”) and (II) to reduce tax distortions (the “blue dividend”) (Karydas and Zhang 2019; de Angelis et al. 2019). In addition, “although most taxes distort incentives, an environmental tax corrects a distortion, specifically the externalities stemming from the overuse of environmental services,” as argued by Pearce (1991), Khan et al., (2021b), Khan et al. (2019c), and Khan et al. (2022a, b). Multiple studies have shown that environmental charges lower carbon dioxide emissions (Miller and Vela 2013; Morley 2012). Environmental taxes reduce carbon emissions and boost the adoption of lower-emissions energy, as shown by Hao et al. (2021), Khan et al. 2022a, b), Khan et al. (2020a, b), and Khan et al. (2019a, b, c, d, e). Taxes on energy resources have the potential to lessen energy demand and, in turn, greenhouse gas emissions (Safi et al. 2021; Shabir et al. 2022). After summarizing the existing literature, many studies examined the effect of different environmental factors on environmental degradation. We also concluded that environmentally related technologies and tax revenues are frequently viewed as important determinants for reducing emission rates. But existing literature has failed to establish the combined role of environmentally related technologies and revenue taxes in environmental degradation by employing the PMG panel ARDL method, thereby presenting an incomplete picture of empirical evidence. Due to the dearth of literature on the role of environmental technologies and revenue taxes for energy and environmental issues, analysis of the role of environmentally related technologies and revenue taxes on CO₂ emission reduction is of critical importance. This study is an effort to fill this gap in the existing literature (Fig. 1). It should be ensured that these technologies and taxes are economically efficient and environmentally friendly.

Research methodology

Utilizing balanced panel data from 36 different OECD nations covering the years 1990–2020, the primary goal of the current study is to evaluate the impact that EG, ERT, FDI Inflows, TO, and ERTs have on CO₂ emissions. The previous research served as the basis for the selection of the factors that would be used in this investigation. To evaluate the extent to which the ecosystem is being degraded, CO₂ has been employed as a proxy (Cowan et al. 2014). Numerous studies have been conducted to

investigate the factors that contribute to CO₂ emissions. Some examples of these studies include Shahbaz et al. (2018), Sheraz et al. (2022), and Fatima et al. (2021). According to the findings of our study, we came up with the following equation:

$$\begin{aligned} \text{Carbon dioxide emission}_{it} &= \beta_0 + \beta_1 \text{Economic Growth}_{it} \\ &+ \beta_2 \text{Environmental Related Technologies}_{it} \\ &+ \beta_3 \text{Foreign Direct Investment Inflows}_{it} \\ &+ \beta_4 \text{Trade Openness}_{it} \\ &+ \beta_5 \text{Environmental Related Tax Revenue}_{it} + \varepsilon_{it} \\ \text{CO}_2 \text{ emission}_{it} &= \beta_0 + \beta_1 \text{EG}_{it} + \beta_2 \text{ERT}_{it} \\ &+ \beta_3 \text{FDI Inflows}_{it} + \beta_4 \text{TO}_{it} + \beta_5 \text{ERT}_{it} + \varepsilon_{it} \end{aligned} \quad (1)$$

Using a panel dataset with time periods $t = 1, 2, 3, \dots, T$ and countries $i = 1, 2, 3, \dots, N$, the following panel ARDL (P, Q, Q, ..., Q1) model is estimated. The data for the study variables were obtained from the OECD's statistics. The list of countries can be found in the Appendix (see Table 9). Data for each variable is obtained from OECD statistics. Particularly, this study selected environmental degradation as a dependent variable, and CO₂ emissions in metric tonnes per capita were used as a proxy, whereas environmentally related taxes and revenues, environmentally related technologies, economic growth, FDI inflow, and trade openness are used as independent variables to get a deeper insight into the selected factors that contribute to environmental degradation. The variables of the study, with their respective proxies that were utilized to measure them, are shown in Table 1.

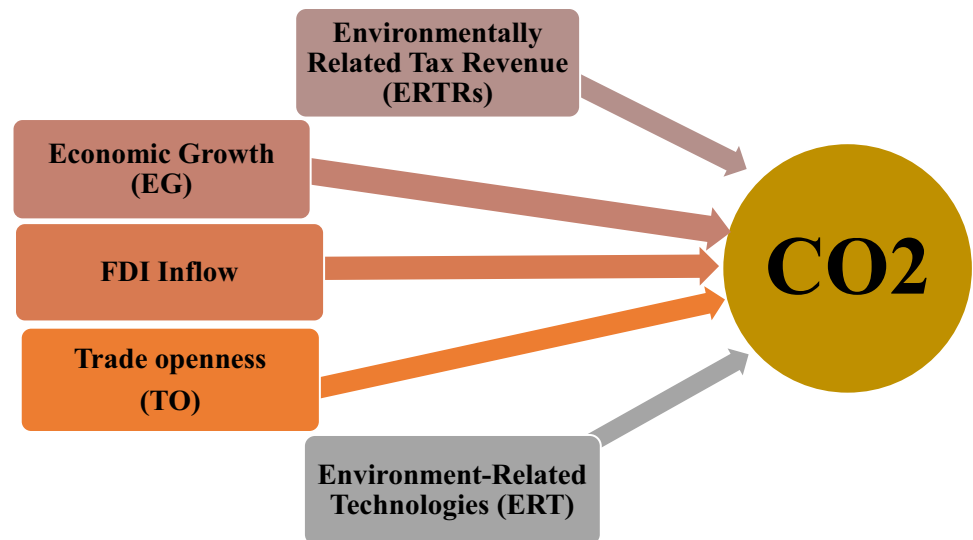
Econometric approach for panel ARDL

Following panel ARDL (P, Q, Q, ..., Q1) model is estimated based on panel data set with time periods $t = 1, 2, 3, \dots, T$ and countries, $i = 1, 2, 3, \dots, N$.

$$\text{CO Emission}_{2it} = \sum_{j=1}^P \lambda_{ij} \text{CO Emission}_{2it-j} + \sum_{j=0}^Q \delta'_{ij} X_{it-j} + \mu_i + \varepsilon_{it} \quad (2)$$

X_{it} (K 1) in panel ARDL (P, Q, Q, ..., Q1) demonstrates the vectors of regressor group i ; i indicates a fixed effect. Scalars are represented in the equation by the coefficients of lagged regression and CO₂, ij , and $-ij$. coefficient vector ($k \times 1$). If the regressors and regressands are cointegrated, the error correction term is applied to all groups of countries. The key feature of cointegrations between regressors and regressand reveals the error correction model, which specifies how deviations from equilibrium affect the short-run dynamics of both regressor and regressand in the system. The error correction equations listed below are based on the panel ARDL (P, Q, Q, ..., Q1).

$$\begin{aligned} \Delta \text{CO Emission}_{2it} &= \varnothing_i (\text{CO Emission}_{2it-1} - \theta' X_{it-1}) \\ &+ \sum_{j=1}^{P-1} \lambda^*_{ij} \Delta \text{CO Emission}_{2it-j} + \sum_{j=0}^{Q-1} \delta'^*_{ij} \Delta X_{it-j} + \mu_i + \varepsilon_{it} \end{aligned} \quad (3)$$

Fig. 1 Theoretical framework

Above equation $\phi_i = -\left(1 - \sum_{j=1}^P \lambda_{ij}\right)$, $\theta_i = \sum_{j=0}^Q \frac{\delta_{ij}}{(1 - \sum_{k=1}^P \lambda_{ik})}$, $\lambda_{ij}^* = -\sum_{m=j+1}^P \lambda_{im}$, $j = 1, 2, 3, \dots, P-1$, and $\delta_{ij}^* = -\sum_{m=j+1}^Q \delta_{im}$, $j = 1, 2, 3, \dots, Q-1$. ϕ_i in the equation represents the speed of adjustments to equilibrium is termed as error correction speed. If the examined error correction (i.e., $\phi_i = 0$), speed of adjustment is equal to zero then there exists no long-term relationship. Based on the notion that study variables in the equation demonstrate return in long-term equilibrium, the error correction component is negative and large. The term θ_i represents long-term relationship between regressand and regressors.

The following equation is based on Eq. (3) for all utilized variables.

Pesaran and Smith (1995) developed the panel data mean group (MG) estimator, in which the slopes of the confidence intervals, intercepts, and error variation change between

countries. Pesaran et al. (1997, 1999) proposed the PMG estimator for the panel data, which associates both the average and pool features. The PMG techniques allow the intercepts, short-term coefficients of the variables, and eventually the error variations to occur in different countries. Furthermore, we investigated the reliance of the cross-sectional CD test using the panel data approach proposed by Pesaran (2004). To evaluate unit root, Im-Pesaran-Shin and Fisher-type tests proposed by Shin and Zhou (2003), and Maddala and Wu (1999) are used. The present study also employed the second-generation panel unit root test, i.e., the CADF (cross-sectional augmented Dicky-Fuller) test developed by Pesaran (2007), to check the CD in the longitudinal dataset. These panel unit root tests perform better and are more robust due to their asymptotic assumptions. The CADF test provides precise information about the series'

$$\begin{aligned} \Delta COEmission_{2it} = & \beta_0 + \phi_{1,i} [COEmission_{2it-1} - \theta'_{2,i} (EG_{it}, ERT_{it}, FDIInflows_{it}, TO_{it}, ERTR_{it})'] \\ & + \sum_{j=1}^{P-1} \lambda_{ij}^* \Delta COEmission_{it-j} + \sum_{j=0}^{Q-1} \delta_{ij}^* \Delta EG_{it-j} + \sum_{j=0}^{Q-1} \delta_{ij}^* \Delta ERT_{it-j} + \sum_{j=0}^{Q-1} \delta_{ij}^* \Delta FDIInflows_{it-j} \\ & + \sum_{j=0}^{Q-1} \delta_{ij}^* \Delta TO_{it-j} + \sum_{j=0}^{Q-1} \delta_{ij}^* \Delta ERTR_{it-j} + \mu_i + \varepsilon_{it} \end{aligned} \quad (4)$$

Table 1 Variable description

Sr. no	Variables	Description	Proxies
1	CO ₂	Environmental degradation	CO ₂ emissions (metric tons per capita)
2	ERTRs	Environmentally related tax revenue	Tax revenue, % of GDP
3	EG	Economic growth	GDP growth (annual %)
4	ERTs	Environmentally related technologies	Number of patents, with fractional country value
5	FDI	FDI inflow	Net inflows as % of GDP
6	TO	Trade openness	Trade (% of GDP)

integration order. Pesaran's (2007) CADF panel stationary test is generally represented by the following equation:

$$\Delta Y_{it} = \beta_i + \delta_i Y_{i,t-1} + \lambda_i \bar{y}_{t-1} + \psi_i \Delta \bar{y}_t + \mu_{it} \quad (5)$$

Adding lag term ($t-1$) in Eq. (5), we get the following equation:

$$\Delta Y_{it} = \beta_i + \delta_i Y_{i,t-1} + \lambda_i \bar{y}_{t-1} + \sum_{j=0}^p \psi_{ij} \Delta \bar{y}_{t-j} + \sum_{j=0}^p *_{ij} \Delta y_{it-j} + \mu_{it} \quad (6)$$

where $\Delta \bar{y} - i$, $t-1$, and $\bar{y} - t-j$ represent the first difference operator and the averages of each cross section's lagged level. The cointegration test proposed by Kao et al. (1999) and Pedroni (1999, 2004) is used to check for cointegration. To select between the PMG and MG estimators, the Hausman test, proposed by Hausman (1978), is employed.

Empirical results and discussion

Results

The Panel ARDL approach is used to validate the influence that economic growth (EG), environmentally related technologies (ERTs), foreign direct investment inflows (FDI inflows), trade openness (TO), and environmentally related tax revenue (ERTRs) have on carbon dioxide (CO₂) emissions. Quantile regression (simultaneous quantile regression and panel quantile regression) is used to examine the robustness of the results.

The findings of the descriptive statistics are described in Table 2. Based on the findings, we can deduce that the average CO₂ emission is 8.597, with the smallest value being 2.171 and the greatest value being 30.362. The findings indicate that the average GDP is 2.508, with its greatest value being 25.176 and its lowest value being −14.839, respectively. The environmental technologies have a maximum value of 10,555.73 and a minimum value of 0.1700, with a value that averages out to be 654.052. The value of foreign direct investment (FDI) inflows ranges from a low of −57.532 to a high of 109.331, with an average of 6.262. TO and environmental revitalization (Envir Reve) have respective minimum and maximum values of 15.810 and −1.530, and 380.104 and 5.360. Their respective averages are 87.069 and 2.387.

Table 3 contains the findings that were obtained from the correlation matrix. According to the findings of a correlation study, CO₂ emissions had a positive link with GDP, RETech, and TO but a negative association with FDI and ENVR among the nations that were sampled. The correlation matrix demonstrates that foreign direct investment (FDI) and Envir Reve both contribute to the reduction of

environmental deterioration in certain nations. while factors such as GDP, ReTech, and TO all contribute to an increased rate of environmental deterioration.

Because cross sections might exhibit the same or opposite characteristics, the estimation of cross-sectional dependence (CD) is the starting point for the analysis of panel data. This can lead to results that are erroneous, biased, and inconsistent. As a result, doing the CD test on the panel data is essential before moving on to the subsequent analysis. The CD test is triggered if there are several geographical implications, externalities, latent shared outcomes, economic structure, finances, social networks, and bilateral shocks. In Table 4, the CD test developed by Pesaran (2004) is used to investigate panel dependence. The CD test substantiates the existence of cross-sectional reliance throughout the whole sample of nations. The result of the CD test contradicts the null hypothesis that there is no cross-correlation, which suggests that the variables under consideration are intertwined. This suggests that changes in the environment in one country may affect the environments of other nations (selected OECD countries) in the panel.

Before applying the econometric techniques for the long and short-run integration, it is common practice to conduct unit root tests on the data to determine whether or not they are stationary (panel ARDL). The conclusions derived from the unit root test are shown in Table 5. The Im-Pesaran-Shin unit root test and the Fisher-type unit root test are the two methodologies that are utilized. To alleviate this concern, this study employs second-generation panel unit root tests such as cross-sectional augmented Dickey-Fuller (CADF) and the cross-sectional Im-Pesaran test developed by Pesaran. The CADF test provides precise information about the integration order of a series of variables. The results of these tests are represented in Table 5. The CADF unit root test results show that ERTs and CO₂ have a unit root problem at level I(0). However, at a 1% significance level, all of the series become stationary after taking their first integration order (I). CADF is appropriate for testing the long-run equilibrium of a series. The results show that all variables

Table 2 Descriptive statistics

Variable	Obs	Mean	Std. dev	Min	Max
CO ₂	1116	8.597	4.296	2.1710	30.362
GDP	1065	2.508	3.358	−14.839	25.176
ERT	1042	654.052	1690.375	0.1700	10555.73
FDI	1072	6.262	14.741	−57.532	109.331
TO	1086	87.069	51.508	15.810	380.104
ERTRs	950	2.387	0.8510	−1.53	5.36

CO₂ carbon dioxide emissions, GDP gross domestic product (a proxy for economic growth), ERTs environmentally related technologies, FDI foreign direct investment inflows, TO is trade openness, ERTRs environmentally related tax revenue

are stable at the level and first difference, indicating that the Panel ARDL model can be used with the variables in question.

Cointegration methods were utilized for the research, which depicted the long-run equilibrium connection of CO₂ emissions with EG, ERT, FDI Inflows, TO, and ERTRs in a selection of sample nations. Panel cointegration approaches produce superior findings compared to model estimates from individual time series. This is due to the fact that model estimation allows for greater freedom in the analysis of time series cross sections, which in turn produces more consistent results. As a result, we utilize two different panel cointegration models, namely the Pedroni test for cointegration (1999, 2004) and the cointegration test that Kao et al. (1999) developed. The two steps (residual-based) cointegration techniques that these two approaches are based on were developed by Engle and Granger (1987). The results of Kao cointegration test are presented in Table 6. The data provide evidence that cointegration does exist across regressors and regressands throughout the sample of OECD nations. In this test, the null hypothesis of no integration was evaluated using an enhanced version of the Dickey-Fuller approach. The alternative hypothesis was also taken into consideration. This test confirms that intercepts exist for cross sections and that homogeneous coefficients exist for first-stage regressors. The findings of both the Pedroni and the Kao tests suggest that cointegration is significant, which indicates the presence of integration among the research variables. This finding is consistent with the hypothesis that integration exists. This study also employed Westerlund (2007) cointegration test because it employs the bootstrap approach to eliminate cross-sectional dependency effects among variables. Table 6 results show that cointegration exists, confirming the long-run relationship between research variables. Significance *P* value confirms the rejection of H₀. This implies the existence of cointegration, which demonstrates that there is a long-term relationship between study variables.

The findings of the pooled mean group ARDL in short-run and long-run elasticities of CO₂ emissions with GDP, ERT, FDI, TO, and ERTRs are summarized in Table 7. The

Table 4 Average correlation coefficient and Pesaran (2004) CD test

Variables	CD test	<i>P</i> value	Corr	Abs(Corr)
CO ₂	38.39	0.000	0.322	0.594
GDP	59.53	0.000	0.503	0.505
ERTs	88.96	0.000	0.744	0.745
FDI	18.43	0.000	0.155	0.245
TO	64.97	0.000	0.536	0.660
ERTRs	12.36	0.000	0.105	0.431

Under the null hypothesis of cross section independence $CD \sim N(0, 1)$

findings indicate that in the short and long runs, there is a correlation that is both positive and significant between CO₂, GDP, and TO. According to these findings, a 1% increase in GDP growth leads to a 1.7007% increase in CO₂ emissions in the short run and a 0.1290% increase in emissions in the long run. On the other hand, both ERT and ERTRs have a negative impact on CO₂ over the short and long terms. This demonstrates that a 1% rise in ERT and ERTRs causes a decrease in CO₂ emissions of −0.1953%, −0.3224%, and −0.8786, −0.8771 over the short run, the medium run, and the long run, respectively. In contrast, foreign direct investment (FDI) has a positive and significant relationship in the short run but a negative relationship in the long run. This demonstrates that a 1% increase in FDI results in a 0.2163% increase in CO₂ in the short run, but a 1% increase in FDI results in a −0.1442% decrease in CO₂ in the long run. At a significance level of 5%, the results of the short-run and long-run analyses, which are represented by panels I and II, respectively, show that all of the variables GDP, ERT, FDI, TO, and ERTRs are statistically significant. The findings of our study are consistent with the previous investigation of Apergis et al. (2021).

Quantile regression, also known as simultaneous regression, is a technique that was used to determine whether or not the data that were evaluated were reliable. Table 8 contains a comprehensive summary of the robustness check QR findings. According to the data, there is a significant inverse correlation

Table 3 Matrix of correlations

Variables	(1)	(2)	(3)	(4)	(5)	(6)
(1) CO ₂	1.000					
(2) GDP	0.025	1.000				
(3) ERTs	0.270	−0.140	1.000			
(4) FDI	−0.018	0.028	−0.123	1.000		
(5) TO	0.159	0.108	−0.293	0.194	1.000	
(6) ERTRs	−0.072	−0.019	−0.296	0.086	0.178	1.000

CO₂ carbon dioxide emissions, *GDP* gross domestic product (a proxy for economic growth), *ERTs* environmentally related technologies, *FDI* foreign direct investment inflows, *TO* is trade openness, *ERTRs* environmentally related tax revenue

Table 5 Panel unit root test

Variables	Im-Pesaran-Shin unit-root test		Fisher-type unit-root test		Pesaran's CADF test	
	At level	First diff	At level	First diff	At level	First diff
CO ₂	3.912	−17.324***	3.912	74.968***	0.337	−4.864***
GDP	−9.944***	−18.337***	22.330***	88.219***	−4.845***	−10.511***
ERT	−0.477	−17.395***	0.847	89.240***	−3.583***	−7.541***
FDI	−10.004***	−20.648***	22.808***	123.756***	−1.306***	−10.094***
TO	0.372	−16.028***	−1.373	54.600***	−1.702***	−4.131***
ERTRs	0.604	−15.169***	2.485**	56.682***	1.516	−3.761***

CO₂ carbon dioxide emissions, GDP gross domestic product (a proxy for economic growth), ERTs environmentally related technologies, FDI foreign direct investment inflows, TO is trade openness, ERTRs environmentally related tax revenue

between FDI inflows and CO₂ emissions in some countries. According to the findings of the SQR, an increase in FDI inflows contributes to a reduction in environmental degradation of 1% and a slowing of environmental deterioration of −0.008%, −0.0239%, −0.0342%, and −0.002% from quantile 25 to quantile 95, respectively, in certain OECD nations. According to the findings of SQR, environmental deterioration and poverty are strongly and positively related in a number of OECD nations. These variables include GDP, ERT, FDI, TO, and ERTRs. While at the 95th quantile, ERTRs have a substantial negative correlation with the degradation of the ecosystem. According to the findings of the study, environmental degradation and EG have a substantial positive relationship. This suggests that a 1% rise in EG is responsible for a 0.1159% increase in environmental degradation in quantile 50 across several nations. The findings reveal that any country's EG requires more modern environmentally related technology, TO, and environmentally related tax revenues;

yet, the impact that it will have on the environment is unavoidable. The enormous demand for these determinants is having a negative impact, all across the world, on the natural environment. In addition to this, the QR is graphically represented in Fig. 2. The graph of ERTs shows a negative trend from the 25th to the 50th quantiles and an appositve trend from the 50th to the 75th. While the graph demonstrates a negative trend in environmental degradation from the 75th to the 95th quantiles, The graph of ERTRs represents a negative trend in environmental degradation from the 25th quantile to the 95th. This indicates that both the variables of interest, ERTs and ERTRs, contribute to decreasing CO₂ emissions and thus stabilizing the quality of the environment.

Discussion

By using the CD test, we begin our analysis by looking at the CD in the study variables. The null hypothesis is rejected as a

Table 6 Panel cointegration test

	Statistics	P-value
Kao cointegration test		
MDF t	1.9660	0.0246
DF t	2.8203	0.0024
ADF t	0.2297	0.0129
UMDF t	0.5071	0.3060
UDF t	1.4485	0.0737
Pedroni cointegration test		
MPP t	5.2481	0.0000
PP t	0.2945	0.3842
ADF t	−20.4996	0.0000
Westerlund test for cointegration		
Variance ratio	−4.1324	0.0000

MDF t modified Dicky Fuller t, DF t Dicky Fuller t, ADF t augmented Dicky Fuller t, UMDF t unadjusted modified Dicky Fuller t, UDF t unadjusted Dicky Fuller t, MPP t modified Phillips-Perron t, PP t Phillips Perron t

Table 7 Pooled mean group ARDL

D.co2	Coef	Std. err	Z	P>z
Short run				
GDP	1.7007	0.3945	4.3100	0.0000
ERT	−0.1953	0.0006	−3.2100	0.0010
FDI	0.2163	0.0431	5.0142	0.0000
TO	0.1404	0.0274	5.1195	0.0000
ERTRs	−0.8786	0.256	−3.4325	0.0000
ECT	−0.3105	0.0613	−5.0660	0.0000
Long run				
GDP	0.1290	0.0100	12.9097	0.0000
ERT	−0.3224	0.0341	−9.4570	0.0000
FDI	−0.1442	0.0195	−7.3876	0.0000
TO	0.6532	0.0515	12.6868	0.0000
ERTRs	−0.8771	0.3158	−2.7770	0.0092
v_cons	0.5414	0.1993	2.7173	0.0070
Hausman chi ²		6.9265		0.4092

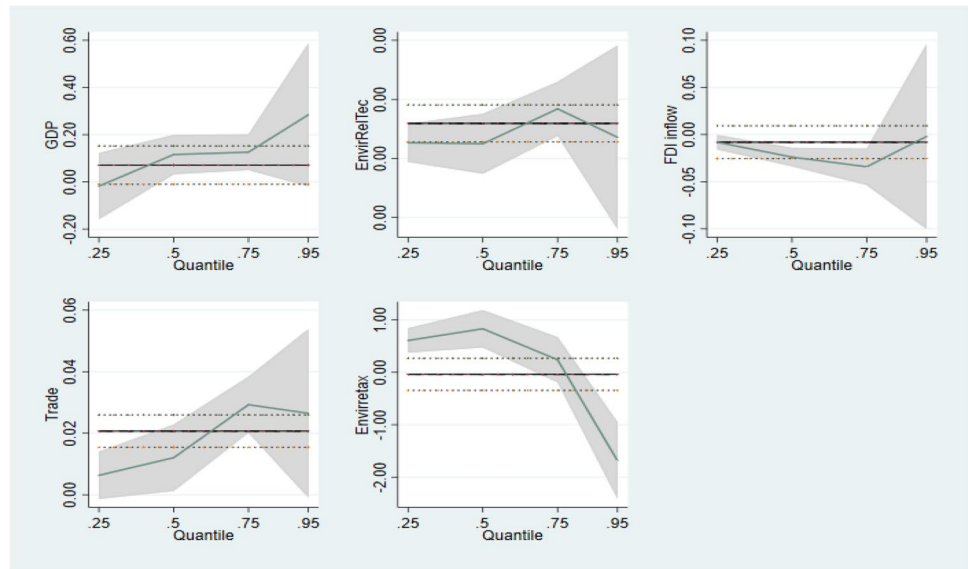
*P < 0.05; **P < 0.01; ***P < 0.001

result of the CD test results in Table 2, which confirm the CD in the panel. The results are consistent with the study of Zaidi et al. (2019). Im-Pesaran-Shin, Fisher-type, and CADF unit root tests have been employed in the current study to examine the unit roots in the variables before applying tests to find long-run parameter estimates. The results of unit roots are illustrated in Table 4. The results show that variables at the level and first difference are stationary. Next, we checked the panel cointegration. This study employed panel cointegration, considering the CD in the data. This study employed Kao and Pedroni cointegration tests to examine the long-run equilibrium (Ouedraogo 2013). The findings of both the Pedroni (1997) and the tests suggest that cointegration is significant, which indicates the presence of integration among the research variables. To examine the existence of a long-run equilibrium between regressors and regressands, this study employed a newly developed PMG (pooled mean group) panel ARDL approach. The PMG is considered an intermediate method between the mean group estimator (MG) and the difference from the mean estimator (DFE) because it combines pooling and averaging (representing the MG estimator and DFE). According to the studies of Alvarado et al. (2018), Cao et al. (2022), Chishti et al. (2021), Dagar et al. (2022a), Dagar et al. (2022b), Dagar et al. (2021), Islam et al. (2021), and Adusah-Poku (2016), coefficients and variances of error may vary between groups, but long-run coefficients must be identical. The study findings demonstrate that a 1% increase in GDP growth leads to a 1.700% and a 0.1290% increase in CO₂ emissions in the short and long runs, respectively. On the other hand, both ERT and ERTs have a negative impact on CO₂ over the short and long term, which indicates that efficient and friendly environmental technologies and taxes help to reduce environmental degradation. These findings support those of Khan et al. (2021c), Muhammad and Khan (2021), Muhammad and Khan (2022), Muhammad et al. (2021), and Boufateh and Saadaoui (2020). They also confirmed that the use of advanced

technologies plays a key role in the mitigation of CO₂ emissions and thus improves the environmental quality. The studies of Oryani et al. (2021), Oryani et al. (2022), Qin et al. (2021), Rehman et al. (2022), Teng et al. (2021), Weimin et al. (2022), Zakari et al. (2021), Rehman et al. (2021), Zhang et al. (2021a, b), and Zia et al. (2021) confirm that tax revenues contribute to lower CO₂ emissions and thus stabilize environmental quality. FDI inflow has a positive and significant relationship in the short run but a negative relationship in the long run. These findings are in line with the studies of Paramati et al. (2016), Khan et al. (2020a, b), Khan et al. (2021a, b, c, d, e, f), and Khan et al. (2021a). At a significance level of 5%, the results of the short run and long run analyses, which are represented by panels I and II, respectively, show that all of the variables, i.e., GDP, ERT, FDI, TO, and ERTs, are statistically significant. The results of our study are in line with those of a previous investigation (Apergis and Payne 2010). We used quantile regression to conduct a more thorough analysis of model estimation at various quantiles, which supported further validation of the reliability of our estimation results. Quantile regression, compared to traditional regression, relies more heavily on the mean and explains the entire conditional distribution of CO₂ emissions and its determinants by identifying quantile points at various points along the conditional distribution. Quantile regression allows determining whether the effects of CO₂ determinants vary across the conditional CO₂ distribution, with an emphasis on countries with low, intermediate, and high CO₂ levels. Table 8 summarizes the QR results. In some countries, FDI and environmental degradation are inversely related. In certain OECD countries, increased FDI reduces CO₂ emissions by 1% and slows environmental deterioration by 0.008%, 0.0239%, 0.0342%, and 0.002%. Environmental degradation and EG are linked in several OECD countries, according to SQR. The 95th quantile ERTs correlate negatively with environmental degradation. A 1% increase in EG causes a 0.1159% increase in environmental degradation in the

Table 8 Robustness check with quantile regression

	SQR			
	Q25	Q50	Q75	Q95
Economic growth	−0.018 (−0.25)	0.1159*** (3.47)	0.1258*** (4.38)	0.2842 (1.88)
Environmentally related technologies	0.0006*** (8.6)	0.0006*** (4.09)	0.0009*** (9.33)	0.0007 (1.66)
FDI inflow	−0.0081** (−2.36)	−0.0239*** (−7.52)	−0.0342 (−1.78)	−0.002 (−0.05)
Trade openness	0.0063* (2.18)	0.0121** (2.56)	0.0293*** (7.00)	0.0265* (2.08)
Environmentally related tax revenue	0.6069*** (4.89)	0.8302*** (5.09)	0.2386 (1.46)	−1.6841*** (−6.28)
_cons	3.3929*** (8.01)	4.1003*** (9.65)	5.7372*** (11.05)	16.883*** (8.90)
Pseudo- R^2	0.0926	0.0787	0.1013	0.129
N	859			

Fig. 2 Graphical representation of QR

quantile 50. Any country's EG requires modern environmental technology, TO, and tax revenues; its environmental impact is inevitable. Trade openness has an impact on the environment. These findings corroborate the findings of Koenker (2004) and Borozan (2019).

Conclusion

In this study, the relationship between environmental degradation (CO_2 emission), economic growth (EG), trade openness (TO), and environmentally related tax revenues (ERTs) in a panel of 36 OECD countries with the most recent dataset spanning from 1990 to 2020 is evaluated. Foreign direct investment (FDI) inflows, environmentally related technologies (ERTs), EG, and TO are the variables under investigation. The PMG estimator is used to investigate the nature of the connection between the various research variables. Cointegration techniques are utilized to assess both the short- and long-run connections between the series of variables. The presence of cointegration between variables may be demonstrated using either the Pedroni or the Kao test. In addition, the method of quantile regression is utilized to examine the robustness of the variables. On the other hand, the Im-Pesaran-Shin unit root test and the Fisher-type unit root test are used in the panel unit root test to determine whether or not the variables of the research are stationary. According to the findings of these methods, all of the variables, both at the level and at the first difference, are stationary. This proves that panel ARDL may be used. The PMG estimator is chosen by contrasting the test results obtained by Hausman with those obtained by the MG estimators. According to the findings of the PMG, both the TO and EG have a beneficial influence on environmental deterioration in the panel nations; however, when it comes to FDI, ERTs, FDI Inflows, and ERTs, these factors have a

negative impact on environmental degradation in the long-term study. While in the short term, EG, FDI, and TO all have strong positive relationships with environmental degradation, ERTs and ERTs have significant relationships that are not positive with CO_2 . The overall findings indicate that demand for environmentally friendly technologies and ERTs are the key factors that determine environmental degradation in the sample countries. These determinants are found to have a significant impact on environmental degradation. Few OECD countries are making an effort to safeguard EG by competing with the developed countries of the globe, which adds to increasing levels of CO_2 emissions and the destruction of the environment. To compete with the current economic challenges, EG in the sample countries must be accompanied by effective environmental policies and regulations. The findings of the study recommend the formulation of suitable plans to encourage environmentally responsible investment for environmental conservation. To find solutions to the economic problems that threaten the ecosystem's long-term viability, policymakers need to enact policies that encourage a climatically stable environment. OECD nations need to enhance public–private partnerships in energy projects to meet the Sustainable Development Goals (SDG) for cost-effective, clean energy, water, and sanitation. These SDGs were established to guide global development over the next 15 years. The use of fossil fuels for economic reasons has been shown to have a positive impact on climate change and environmental damage in countries that are members of the OECD. EG is attainable with the development of infrastructure and the effective utilization of energy resources based on technological advancements. Policymakers have a responsibility to encourage investment in the solar, thermal, and wind power sectors. They should develop policies that boost economic growth, environment-related technology, carbon levies, trade, and foreign direct investment inflows to produce clean energy and protect the environment to

accomplish the SDGs by the year 2030. Policies that encourage the development of environmentally friendly technology, economic expansion, trade openness, environmentally related tax revenues, and foreign direct investment inflows to support green infrastructure and energy generation are all advocated. Because CBCO2 is tied to the import and export of every economy, the trade balance should also be revised to favor those economies with the lowest carbon emissions. The nations that make up the OECD should encourage environmental legislation and provide financial incentives to investors who want to put their money into renewable energy projects to improve the environment. In addition, the government ought to encourage strategic collaboration with foreign economies on a variety of levels to advance

environmentally friendly innovations. Despite the considerable contributions made, the study has several limitations, some of which may lead to new lines of inquiry in the near or distant future. First, due to a paucity of data, the scope of the study is limited to 30 years. It is possible that, in the future, re-examining the model with a bigger panel will produce more generalizable results. The second limitation of this research is that although the pooled mean group panel ARDL strategy was utilized, various econometric methods are available to researchers who wish to investigate the influence of environmental factors. Third, the OECD countries were the exclusive focus of this research; however, research may be undertaken in other nations as well based on the readily available data.

Appendix

Table 9 List of sample countries

Austria	Spain	Ireland	Greece
Hungary	Estonia	Poland	Mexico
New Zealand	Lithuania	Czech Republic	USA
Australia	Switzerland	Israel	Germany
Italy	France	Sweden	Norway
Netherland	Luxembourg	Canada	UK
Belgium	Slovenia	Japan	Denmark
Iceland	Finland	Slovak Republic	Korea
Portugal	Latvia	Chile	Turkey

Table 9

Author contribution Conceptualization and methodology, Nudrat Fatima and Zheng Yanting; Methodology, writing—original draft, Nudrat Fatima; supervision, Zhang Yanting and Ni Guohua. All authors read and agreed to the published version of the manuscript.

Data availability The datasets generated and analyzed during 1990 to 2020 the current study is available in the OECD Statistics <https://stats.oecd.org/>.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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