Financial Innovation

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Does financial development moderate the link between technological innovation and environmental indicators? An advanced panel analysis

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Abstract

This study analyzes the role of financial development (FD) on the impact of technological innovation (TI) on six environmental quality indicators for the 25 economies that are part of the Organization for Economic Cooperation and Development for the period from 2000 to 2019. We use a two-step dynamic generalized method of moments approach to understand this relationship. The results show that FD augments the positive effects of TI on four of the six environmental indicators, namely ecological footprint, adjusted net savings, pressure on nature, and environmental performance. However, no significant effects on environmental sustainability and environmental vulnerability indices were found. When considering all of the environmental quality indicators, TI appears to enhance environmental quality. We find evidence to support the existence of the environmental Kuznets curve in the context of each environmental indicator and economic growth. Moreover, FD and energy consumption appear to accelerate environmental degradation. Based on these results, FD should be viewed as an important parameter in designing policies for innovation to achieve the goal of net-zero carbon emissions.

Highlights

- Technological innovation and environmental quality nexus is studied.
- The moderating role of financial development is analyzed.
- Six different environmental quality indicators are used for OECD countries.
- Financial development intensifies the environmental benefits of innovation.
- The EKC hypothesis is confirmed for all six environmental indicators.

Keywords: Technological innovation, Financial development, Two-step dynamic Sys-GMM estimator, Environmental quality indicators, Environmental sustainability

JEL Classification: C33, O31, O44, Q55, Q56

Introduction

In recent years, increasing global temperatures caused by increased greenhouse gas emissions, especially carbon dioxide (CO_2) resulting from economic activities, have become a global concern (Ahmed et al. 2019). This issue is of paramount importance; indeed, achieving economic growth along with a clean, sustainable environment is one of the main challenges of this century (Ahmed et al. 2021a). This has attracted attention from environmental economists worldwide as they strive to find a path toward sustainable economic growth. Accordingly, many studies have examined the relationship between economic growth and environmental sustainability over recent decades.

In this context, numerous environmental quality indicators (EQIs) have been proposed and applied in economics modeling (Fakher et al. 2023, 2022), including the ecological footprint index (EFI) (Sultana et al. 2022), environmental performance index (EPI) (Musa et al. 2021), adjusted net savings (ANS) (Salahuddin and Gow 2019), environmental sustainability index (ESI), environmental vulnerability index (EVI) (Fakher et al. 2021b), and pressure on nature (PN) index (Asici 2013). These empirical studies show varying levels of development across regions and nations may have different, contrasting effects on environmental quality (EQ). Inconsistencies in the findings in the literature confirm that the choice of the dependent variable in measuring EQ can have an impact on the effects of regressors used. Thus, selecting an appropriate variable to represent EQ is an important challenge.

In addition to economic growth, other crucial factors can influence the environment. Among them, FD and technological innovation are of paramount importance. Technological innovation (TI) has been the subject of many studies; however, there are controversies about its environmental effects. TI contributes to economic development, productivity, and advancements in technology. Improvements in technology can play an important role in reducing environmental degradation (ED) (Ullah et al. 2021). Innovation-based technological advancement can help to achieve a low-carbon economy by increasing accessibility and adoption of green energy through technologies in the field of renewable energy (Ahmad et al. 2020). Green energy technologies, such as solar panels, effectively curb carbon emissions (Kou et al. 2022). Thus, innovation improves ecological quality by boosting renewable energy generation and consumption.

FD can have both desirable and undesirable impacts on the environment (Kihombo et al. 2021). Despite the many studies on this topic, there is still a lack of clarity about the environmental effects of FD. On one hand, FD helps businesses to expand, which can increase energy consumption (EC), waste, and land usage. FD also helps to meet the financial needs of more individuals, enhancing overall purchasing power which increases resource consumption and worsens ED (Kihombo et al. 2021). Conversely, FD can increase funding for green projects that enhance EQ (Acheampong 2019).

In addition to the direct connection between FD and EQ, FD is known to affect TI. Thus, FD could indirectly affect the environment through the TI channel (Fakher et al. 2021a). For example, FD provides a way for societies to benefit from modern technology and environmentally-friendly clean manufacturing that improves regional and global environmental sustainability (Acheampong 2019). In addition, FD can lead to technological advancement that can lessen resource use. This, in turn, can reduce ED (Ahmed et al. 2021b). Also, enhancing technology in the financial sector contributes to economic

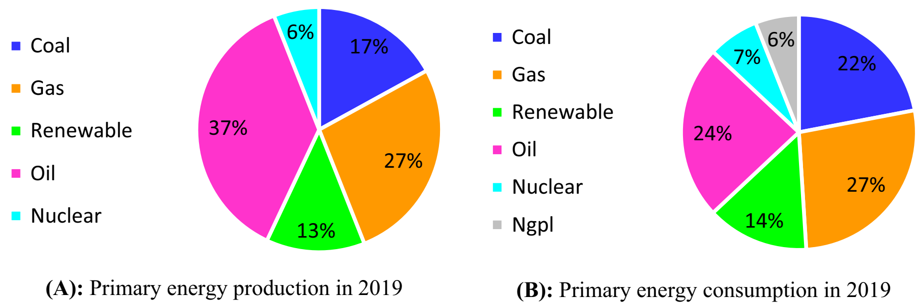


Fig. 1 Consumption and production of primary energy in Organization for Economic Cooperation and Development (OECD) countries. *Source*: IEA (2019)

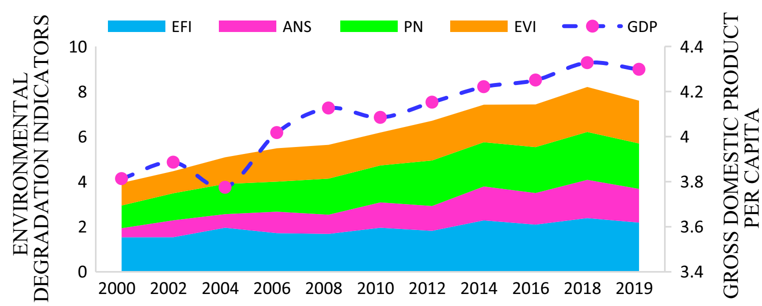


Fig. 2 Trends of EFI, ANS, PN, and EVI (environmental degradation indicators) against gross domestic product per capita (GDP_{PC}) for OECD nations. *Source*: World Bank (2019)

growth by reducing costs and boosting efficiency and performance in financial entities (Kou et al. 2021). This positive impact of financial technology on growth can therefore indirectly promote ecological quality by stimulating better environmental laws and innovative technology (Ahmed et al. 2021b). These arguments highlight the need to understand the interaction between FD and TI as a determinant of EQ, which has largely been ignored in the literature. Hence, this study analyzes the moderating impact of FD on the environmental effects of TI in Organization for Economic Cooperation and Development (OECD) countries.

We chose a panel of OECD economies for this study for the following reasons: First, according to the World Bank (2019), OECD countries accounting for approximately 63% of the world's GDP, suggesting that these countries consume well over half of the world's limited resources. Second, the increase in energy demand (total global energy consumption), which requires the use of fossil fuels, comes primarily from OECD countries; roughly 73% of EC in these countries is from non-renewable sources (27% gas, 22% coal, and 24% oil). Third, over the past three decades, CO_2 emissions have increased by about 61% around the globe, with OECD countries accounting for one-third of global carbon emissions (IEA 2019). These emissions are considered one of the main sources climate change, which threatens the entire planet. Figure 1 shows primary EC and production in these countries.

Lastly, as shown in Figs. 2 and 3, the economic growth seen over the period covered by this study was accompanied by an increase in ED (based on four ED indicators used in the analysis) and a reduction in the quality of the environment (based on two

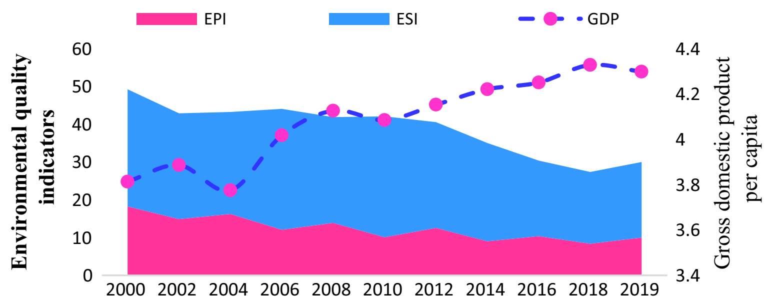


Fig. 3 Trends of EPI and ESI (environmental quality indicators) against gross domestic product per capita (GDP_{PC}) for OECD nations. *Source*: World Bank (2019)

EQ indicators) for the selected OECD economies. Based on this, it is important to understand the connections between EQ with variables such as economic growth, FD, and TI in developing useful environmental strategies.

Against this backdrop, our research contributes to the existing body of literature in several ways: First, to the best of our knowledge no previous study has analyzed the combined influences of FD and TI on EQ. Thus, the theoretical and practical novelty of this study lies in the approach used to scrutinize FD's indirect impacts on the environment through the channel of TI. In our opinion, our results can help policymakers in making important economic and environment-related policy decisions. Second, we focus on the OECD countries with the highest levels of EC and environmental pollution (Lasisi et al. 2022) so that the results can indicate ways to help limit global ED. Third, this study is the first to empirically analyze the moderating role of FD in EQ and TI under the EKC framework (which posits a relationship between various indicators of ED and per capita income). Third, we use six dependent variables, namely four indicators of ED (EFI, ANS, PN, and EVI) and two indicators of EQ (EPI and ESI). Fourth, the results show both theoretically and practically how FD helps the environment by reducing emissions through the channel of TI. Focusing on the viewpoint of EQ, we scrutinize the contribution of FD in determining the impressionability of EQIs under TI conditions, which broadens the research's scope. Finally, econometrically, the reliable two-step Sys-GMM approach is applied in this research. The choice of this method is motivated by the fact that this technique can produce results robust to numerous panel data problems. Considering the economic issues involved and their environmental consequences, the findings in this study could help to formulate appropriate economic and environmental policies.

The principal research objective of this study is to understand the moderating role of FD in the TI-EQI nexus in the presence of appropriate control variables, including economic growth, the square of economic growth (under the EKC framework), and energy consumption using panel data for 25 OECD economies. In this context, we focus on answering the following questions: (i) Is there a link between TI and the EQIs; (ii) What is the moderating role of FD in the TI and EQI nexus; (iii) How does FD influence the EQIs; (iv) How do economic growth and the square of economic growth influence the EQIs; and (vi) What is the role of energy consumption in EQIs? The research fills a large gap in the literature examining OECD countries not only in connection with the important role of FD in TI and EQ connections but also with respect to the crucial pattern of EKC.

The remainder of this study is organized as follows. A review of the existing literature is presented in "A review of related literature" section. In "Data and methodology" section explains our research data and methodology, while "Results" section discusses empirical results. In "Conclusions and recommendations" section offers conclusions and policy suggestions.

A review of related literature

Here we discuss environmental indicators employed in previous empirical studies and the effects of various variables on EQ. Several EQIs have been developed and used in economic-environmental models. For example, Murshed et al. (2021) and Ahmed et al. (2019) use EFI in their studies on South Asia, Musa et al. (2021) adopt EPI in their study of 28 countries in the European Union, Ganda (2019) and Salahuddin and Gow (2019) use ANS to analyze OECD countries and 11 selected countries, respectively, Fakher et al. (2021b) use ESI and EVI in selected groups of Organization of the Petroleum Exporting Countries (OPEC) and OECD countries, and Asici (2013) uses PN for 213 countries.

Given that economic variables play a critical role in EQ, many previous studies address the environmental impact of these variables using various econometric techniques and environmental indicators. A summary of these studies is presented in Tables 1 and 2.

Table 1 An outline of empirical studies on economic growth-ED nexus

Author/s	Period	Country	Method	Indicator/s	Result
Fakher et al. (2023)	1994–2019	OPEC	DSURE	EFI, ANS, PN, EVI	N-shaped
Fakher et al. (2023)	1994–2019	OPEC	DSURE	EPI, ESI	Inverted N-shaped
Udeagha and Breitenbach (2023a, b)	1960–2020	South Africa	ARDL	CO2	EKC
Chishti et al. (2023)	1990–2017	Pakistan	NARDL	CCO2e	Linear (Positive)
Safi et al. (2022)	1990–2018	OECD	SDM	CO2	Linear (Positive)
Imran et al. (2023)	1999–2018	China	SEM	ICTIP	Linear (Positive)
Wahab (2021)	1990–2018	G-7	ARDL	CO2	Linear (Positive)
Hao et al. (2021)	1991–2017	G7	CS-ARDL	CO2	EKC
Pata (2021)	1980–2016	USA	CCT	CO2, EFI	EKC
Saud et al. (2020)	1990–2014	OBOR	PMG	EFI	Linear (Positive)
Usman et al. (2020)	1985–2014	USA	ARDL	EFI	U-patterned
Allard et al. (2018)	1994–2012	74 countries	PQR	CO2	N-shaped
Destek and Sinha (2020)	1980–2014	OECD	FMOLS-MG	EFI	Inverted U-shaped
Danish (2019)	1992–2013	BRICS	GMM	EFI	N-patterned
Anwar et al. (2021)	1991–2018	ASEAN	MMQR	CO2	EKC, Inverted N-shaped
Rana and Sharma (2019)	1982–2013	India	ARDL	CO2	Inverted N-shaped
Godil et al. (2020)	1986–2018	Turkey	Quantile ARDL	EFI	U-shaped

OPEC Organization of the Petroleum Exporting Countries, *DSURE* Dynamic Seemingly Unrelated Regression Equations, *SDM* Spatial Durbin Model, *SEM* Spatial Error Model, *ICTIP* Completed Industrial Pollution Treatment Investment, *GMM* system generalized method of moments, *CS-ARDL* Cross-Sectionally Augmented Autoregressive Distributive lag, *NARDL* Non-linear Augmented Autoregressive Distributive lag, *CCT* Combined cointegration test, *OBOR* one-belt-one-road initiative, *USA* United States of America, *PMG* pooled means group, *PQR* panel quantile regression, *BRICS* Brazil, Russia, India, China, South Africa, *MMQR* Method of Moments Quantile Regression, *FMOLS* fully modified ordinary least squares, CO_2 Carbon dioxide, *CCO2e* Consumption-based carbon dioxide emissions, *ASEAN* Association of Southeast Asian Nations

Table 2 A summary of empirical studies on FD, EC, and TI–EQ nexus

Author/s	Period	Country	Method	Indicator/s	Result
EQ–FD nexus					
Udeagha and Breitenbach (2023a)	1960–2020	South Africa	ARDL	CO2	Positive
Nwani and Omoke (2020)	1971–2014	Brazil	DARDL	CO2	Negative
Ibrahiem (2020)	1971–2014	Egypt	ARDL	CO2	Positive
Aluko and Obalade (2020)	1985–2014	35 SSA	AMG	CO2	Negative
Acheampong (2019)	2000–2015	46 African countries	Dynamic sys-GMM	CO2	Positive
Charfeddine and Kahia (2019)	1980–2015	MENA	PVAR	CO2	Insignificant
Salahuddin and Gow (2019)	1980–2016	Qatar	ARDL	EI, ANS	Insignificant
EQ–EC nexus					
Udeagha and Breitenbach (2023a, b)	1960–2020	South Africa	ARDL	CO2	Positive
Khan et al. (2020)	1965–2015	Pakistan	ARDL	CO2	Positive
Pata (2021)	1980–2016	USA	CCT	CO2, EFI	Positive
Ozcan et al. (2020)	2000–2014	OECD	PVAM	EPI	Positive
Destek and Sinha (2020)	1980–2014	OECD	FMOLS-MG	EFI	Positive
EQ–TI nexus					
Udeagha and Breitenbach (2023a, b)	1960–2020	South Africa	ARDL	CO2	Negative
Safi et al. (2022)	1990–2018	OECD	SDM	CO2	Insignificant
Wahab et al. (2022)	1995–2018	BRICS	SDM	CO2	Positive
Wahab et al. (2021)	1996–2017	G-7	CS-ARDL	CO2	Negative
Adebayo et al. (2021)	1990–2018	Brazil	ARDL—DOLS	CO2	Negative
Ibrahim and Ajide (2021)	1990–2018	G-20	AMG—CCEMG	CO2	Negative
Usman et al. (2020)	1990–2017	APEC	FGLS-AMG	EFI	Positive
Yang et al. (2021a)	1990–2016	BICS	DSUR-FMOLS	EFI	Positive
Chen and Lee (2020)	1996–2018	96 countries	SEM	CO2	Insignificant
Samargandi (2017)	1970–2014	Saudi Arabia	ARDL	CO2	Insignificant

EQ Environmental Quality, *EC* Energy Consumption, *TI* Technological Innovation, *SDM* Spatial Durbin Model, *SSA* Sub-Saharan Africa, *AMG* Augmented Mean Group, *PVAR* Panel Vector Autoregressive, *BEM* Big Emerging Markets, *SEM* Spatial Econometric Models, *IV-GMM* Instrumental Variable Generalized Method of Moments, CO_2 Carbon Dioxide, *DSUR* Dynamic Seemingly Unrelated Regression, *FMOLS* Fully Modified Ordinary Least Squares, *BICS* Brazil, India, China, and South Africa, *ARDL* Autoregressive Distributed Lag

One of the main subjects of the literature on environmental economics is the nexus of economic growth and EQ based on EKC theory. Some relevant studies that focus on this issue are presented in Table 1, and we identify three main points regarding these studies as follows: First, various econometric techniques are used in these studies that cover different periods to detect the presence of the EKC. Second, environmental indicators such as EFI and CO_2 are largely used to represent environmental deterioration. Third, the findings across these studies are contradictory. Table 2 summarizes the literature on the effects of FD, EC, and TI on EQ.

Given the significant contributions of FD, EC, and TI on EQ, various studies have addressed the role of these parameters. Table 2 presents a summary of some of these key studies showing that the impacts of these variables on EQ are often inconsistent. This is a significant challenge in the environmental economics literature and has attracted the attention of several researchers. It is clear that most studies use CO_2 or EFI while the use of other indicators to represent EQ is minimal. Hence, it is important to analyze the nexus of these variables with various EQIs simultaneously and compare the results. In addition, none of the previous studies examine the moderating role of FD in the context of the TI and EQ nexus. Addressing this issue and understanding the impacts of these parameters on six environmental indicators simultaneously will help policymakers and authorities to develop more appropriate policies to improve EQ.

Data and methodology

This section explains the variables used in the study and explains the research methodology and the characteristics of the economic-environmental model.

Data and variables

We use panel data for 25 OECD countries over the period from 2000 to 2019. The countries are selected based on data availability for the environmental performance and environmental sustainability variables used. The independent variables include EC, TI, economic growth, and FD. The environmental indicators used as dependent variables are ecological footprint, adjusted net saving, environmental sustainability, PN, environmental vulnerability, and environmental performance.[1] Table 6 provides the variables' names, descriptions, symbols, and sources (see "Appendix").

Research methodology

As noted above, we use panel data from 25 countries. If a dependent variable emerges as a lagged variable, the OLS becomes an unsuitable estimation technique. However, due to the possibility of estimating larger variances for the computed coefficients using the 2SLS estimator, a known problem in selecting this modeling approach, the estimations may not be statistically significant (Arellano and Bond 1991). Thus, we follow Arellano and Bond (1991) who propose GMM as a solution for the above-mentioned problems. Furthermore, GMM was utilized because the cross-sections (N) are greater than the number of periods (T), as N = 25 and T = 20. Since methods such as the GMM estimator are less efficient than the two-step System GMM, we use the two-step System GMM estimator to increase the reliability of our results (Blundell and Bond 1998).

Theoretical background and model construction

As mentioned in describing the principal research objective of this study, we adopt the EKC framework. The EKC hypothesis initially proposed by Kuznets (1955) posits an inverted U-shaped connection between income inequality and economic growth. This hypothesis has received significant attention in the literature and some studies suggest that the connection between economic growth and environmental deterioration exhibits the same inverted U-shaped relationship. The Kuznets Curve was first applied to EQ research in the 1990s (Grossman and Krueger 1993, 1995; Panayotou 1993). Accordingly, the EKC postulates that ED initially increases due to the scale effect when a country's economic growth is low but gradually decreases as economic growth increases and technique and composition impacts arise (Awaworyi Churchill et al. 2018). EKC-based

[1] For more details on the environmental indicators, see Fakher et al. (2021a, b).

models are widely used in environmental economics to reveal the determinants of ED and EQ (e.g., Kızılgöl and Öndes 2022; Danish and Erdogan 2022; Ullah et al. 2022; Yang et al. 2021b; Zafar et al. 2019). Following these studies, we include both GDP and its square in our model to explore EKC. Notably, when a measure of ED is used the inverted U-shaped relationship will confirm the EKC, but when a measure of EQ is the dependent variable, a U-shaped relationship will confirm the EKC.

Based on the arguments provided in previous sections and following Aluko and Obalade (2020) and Fakher et al. (2021a, b), the research model in this study is specified as follows:

$$lnEQI_{it} = \alpha_0 + \delta lnEQI_{i,t-1} + \theta lnX_{it} + \varepsilon_{it} \tag{1}$$

where i depicts the country ($i = 1, \ldots, n$), and t represents the year ($t = 2000, \ldots, 2019$). $EQIs_{it}$ is the set of EQ indicators for country i at time t, X_{it} represents the explanatory variables (factors that determine EQ), and ε_{it} is the error term. To investigate the reaction of EQIs to the interactive impact of TI and FD given the level of EC, per capita GDP, and the square of per capita GDP, Eq. (1) is rewritten as Eq. (2):

$$\begin{aligned} LnEQIs_{it} = &\alpha_0 + \beta_1 LnEQIs_{i,t-1} + \beta_2 LnFD_{it} \\ &+ \beta_3 LnTI_{it} + \beta_4 Ln(TI_{it} \times FD_{it}) \\ &+ \beta_5 LnGDP_{it} + \beta_6 LnGDP_{it}^2 + \beta_7 lnEC_{it} + \varepsilon_{it} \end{aligned} \tag{2}$$

The strong theoretical underpinnings of the variables used in the literature are the primary reason for including them in Eq. (2). *FD* represents financial development. Based on Fakher et al. (2023), the linkage between FD and EQ is expected to be negative, i.e., $\beta_2 = \frac{d(EQIs_{it})}{dFD_{it}} < 0$. *TI* is technological innovation, which is crucial for controlling environmental pollution. Following Wahab et al. (2022) and Wahab (2021), TI's association with EQ is expected to be positive, i.e., $\beta_3 = \frac{d(EQIs_{it})}{dTI_{it}} > 0$. $TI_{it} \times FD_{it}$ (the interaction between FD and TI), which can be a pivotal factor in controlling ED, is expected to be directly linked with EQ, i.e., $\beta_4 = \frac{d(EQIs_{it})}{d(TI_{it} \times FD_{it})} > 0$. GDP and GDP^2 represent economic growth and the square of economic growth, respectively. According to Fakher and Inglesi-Lotz (2022), we can infer that GDP and GDP^2 are expected to have indirect and direct linkages with environmental pollution levels, respectively, i.e., $\beta_5 = \frac{d(EQIs_{it})}{dGDP_{it}} < 0$ and $\beta_6 = \frac{d(EQIs_{it})}{dGDP_{it}^2} > 0$. Finally, *EC* represents energy consumption, considered to be one of the most influential variables in increasing environmental pollution. Following Fakher et al. (2023) and Wahab et al. (2022), EC is expected to reduce EQ, i.e., $\beta_7 = \frac{d(EQIs_{it})}{dEC_{it}} < 0$. *EQIs* summarizes the indicators of EQ. To achieve the objective of the study, Eq. (2) is modified to form Eqs. (3)–(8).

$$\begin{aligned} Model\ 1: \quad LnEFI_{it} = &\alpha_0 + \alpha_1 LnEFI_{it-1} + \alpha_2 LnFD_{it} \\ &+ \alpha_3 LnTI_{it} + \alpha_4 Ln(TI_{it} \times FD_{it}) \\ &+ \alpha_5 LnGDP_{it} + \alpha_6 LnGDP_{it}^2 + \alpha_7 lnEC_{it} + \varepsilon_{it} \end{aligned} \tag{3}$$

$$\begin{aligned} Model\ 2: \quad LnESI_{it} = &\beta_0 + \beta_1 LnESI_{it-1} + \beta_2 LnFD_{it} \\ &+ \beta_3 LnTI_{it} + \beta_4 Ln(TI_{it} \times FD_{it}) \\ &+ \beta_5 LnGDP_{it} + \beta_6 LnGDP_{it}^2 + \beta_7 lnEC_{it} + \nu_{it} \end{aligned} \tag{4}$$

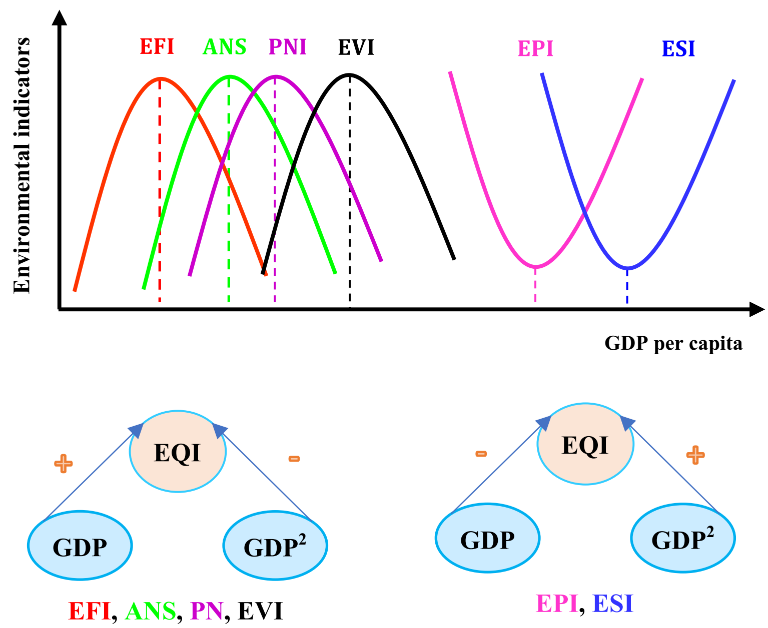


Fig. 4 Expected signs between GDP per capita and EQIs. *Source*: Provided by the authors

$$\begin{aligned} Model\ 3: \quad LnEPI_{it} = & \lambda_0 + \lambda_1 LnEPI_{it-1} + \lambda_2 LnFD_{it} \\ & + \lambda_3 LnTI_{it} + \lambda_4 Ln(TI_{it} \times FD_{it}) \\ & + \lambda_5 LnGDP_{it} + \lambda_6 LnGDP_{it}^2 + \lambda_7 lnEC_{it} + \vartheta_{it} \end{aligned} \tag{5}$$

$$\begin{aligned} Model\ 4: \quad LnEVI_{it} = & \xi_0 + \xi_1 LnEVI_{it-1} + \xi_2 LnFD_{it} \\ & + \xi_3 LnTI_{it} + \xi_4 Ln(TI_{it} \times FD_{it}) \\ & + \xi_5 LnGDP_{it} + \xi_6 LnGDP_{it}^2 + \xi_7 lnEC_{it} + \tau_{it} \end{aligned} \tag{6}$$

$$\begin{aligned} Model\ 5: \quad LnANS_{it} = & \varphi_0 + \varphi_1 LnANS_{it-1} + \varphi_2 LnFD_{it} \\ & + \varphi_3 LnTI_{it} + \varphi_4 Ln(TI_{it} \times FD_{it}) \\ & + \varphi_5 LnGDP_{it} + \varphi_6 LnGDP_{it}^2 + \varphi_7 lnEC_{it} + \pi_{it} \end{aligned} \tag{7}$$

$$\begin{aligned} Model\ 6: \quad LnPN_{it} = & \delta_0 + \delta_1 LnPN_{it-1} + \delta_2 LnFD_{it} \\ & + \delta_3 LnTI_{it} + \delta_4 Ln(TI_{it} \times FD_{it}) \\ & + \delta_5 LnGDP_{it} + \delta_6 LnGDP_{it}^2 + \delta_7 lnEC_{it} + \upsilon_{it} \end{aligned} \tag{8}$$

In the context of the EKC, the possible associations between GDP and the six environmental indicators are shown in Fig. 4. Notably, GDP can have an inverted U-shaped connection with the four indicators of ED, namely PN, EFI, ANS, and EVI, while a U-shaped connection is expected for the EQ indicators EPI and ESI, confirming the EKC framework. These expected relationships will satisfy the EKC theory, which expects improvement in EQ at a high level of GDP.

Results

In this section, we present and discuss the results of the models defined above.

Table 3 Summary statistics analysis of EQIs (dependent variables)

Des. Stat	ANS	EFI	EPI	ESI	EVI	PN
Mean	2.165215	4.195194	6.819044	36.96436	294.6067	12.78455
Max	5.648086	16.66270	17.71566	71.00000	382.0000	85.55836
Min	0.236617	0.654458	0.000283	14.00000	201.0000	0.913675
SD	1.094643	3.930305	5.384240	12.54867	42.38793	10.97835
CV	0.505559	0.936859	0.789589	0.33948	0.14388	0.85872

SD and CV represent the standard deviation and the countries' variation coefficients, respectively

Table 4 Summary statistics of economic variables (independent variables)

Des. Stat	GDP	FD	EC	TI
Mean	41,578.90	51.1844	4531.308	8.350
Max	111,968.3	266.6564	18,178.14	12.024
Min	8947.74	0.5914	1240.166	5.312
SD	21,959.22	40.2827	2810.624	1.228
CV	0/53	0.78	0.62	0.15

Statistical analysis

Tables 3 and 4 present various descriptive statistics for the EQIs and other variables. The coefficients of variation in Table 4 show that ecological footprint, PN, and environmental performance have the highest variation relative to the other indicators. Among the countries included in the study, the EFI and EVI have the highest and the lowest variation coefficients, respectively.

As shown in Table 4, FD and EC have the highest variations compared to the other variables. Among these countries, FD and TI have the highest and the lowest variation rates, respectively.

Research model estimation

In this section we discuss the main outcomes regarding the six EQIs (the dependent variables in models 1 to 6) shown in Table 5. The findings were analyzed in three parts.

First, we discuss the EFI, ANS, and PN as the dependent variables, as shown in Table 5 for models 1, 5, and 6, respectively. The results show that EC has a positive and significant relationship to environmental pollution; in other words, increasing EC is associated with ED in OECD countries. Specifically, a one percent increase in EC implies an increase in ED of 0.438%, 0.050%, and 0.070% as measured by EFI, ANS, and PN, respectively. To explain this result, we note that many of the OECD countries are among the most industrialized and developed in the world (Lasisi et al. 2022). They consume a high level of natural resources to achieve economic growth that relies heavily on pollution-intensive industries (Fakher et al. 2023). Thus, ED is increasing in this group of countries. This result matches the findings in Fakher et al. (2023), Wahab et al. (2021), and Pata (2021), who find that EC has a negative influence on EQ.

Table 5 Results of dynamic assessment through Two-Steps Sys-GMM

Models Ind. Vars	Model 1 Dep. Var.: EFI	Model 2 Dep. Var.: ESI	Model 3 Dep. Var.: EPI	Model 4 Dep. Var.: EVI	Model 5 Dep. Var.: ANS	Model 6 Dep. Var.: PN
L. dep. var	0.553* (0.000)	0.96* (0.000)	0.342* (0.000)	0.914* (0.000)	0.811* (0.000)	0.680* (0.000)
LnEC	0.438* (0.000)	− 0.215** (0.001)	− 0.582* (0.000)	0.010* (0.000)	0.050* (0.000)	0.070* (0.000)
LnFD	0.171** (0.038)	− 0.056** (0.018)	− 0.152* (0.000)	0.004** (0.002)	0.070* (0.000)	0.024** (0.002)
LnTI	− 0.020** (0.002)	0.447* (0.000)	0.404* (0.000)	− 0.023* (0.000)	− 0.019** (0.001)	− 0.080** (0.001)
lnGDP	0.97* (0.000)	− 0.789** (0.003)	− 1.017** (0.005)	0.812** (0.001)	1.028* (0.000)	1.173* (0.000)
ln GDP ^{2}	− 0.017** (0.001)	0.012* (0.000)	0.022** (0.001)	− 0.061* (0.000)	− 0.041* (0.000)	− 0.069* (0.000)
EKC Shape	Inverted U-shape	U-shape	U-shape	Inverted U-shape	Inverted U-shape	Inverted U-shape
LnTI × LnFD	− 0.178** (0.028)	0.022 (0.062)	0.069** (0.003)	0.013 (0.089)	− 0.062** (0.003)	− 0.074** (0.011)
Interactive effect	Increasing	Increasing	Increasing	Decreasing	Increasing	Increasing
Diagnostic tests						
Sargan Test (*p* value)	25.359 (1.000)	28.678 (1.000)	26.350 (1.000)	25.793 (1.000)	27.010 (1.000)	25.710 (1.000)
AR (1) (*p* value)	− 3.265 (0.001)	− 1.257 (0.202)	− 1.561 (0.118)	− 3.393 (0.000)	− 4.148 (0.000)	− 2.650 (0.008)
AR (2) (*p* value)	0.891 (0.741)	1.126 (0.259)	1.247 (0.212)	0.457 (0.647)	1.350 (0.179)	0.801 (0.419)

Numbers in parentheses are *P* values

*, **The levels of significance at 1% and 5% respectively. L. dep. var. denotes Lagged-dependent variables

Second, we can see that the coefficients of GDP and the square of GDP are significantly positive and negative, respectively, suggesting that economic growth initially increases ED, then after reaching a threshold it decreases ED. In other words, the relationship between economic growth and ED follows an inverted U-shaped curve for the OECD countries in the study. OECD countries have the highest EC index levels (Lasisi et al. 2022); thus, to curb EC used to support their growth, many of these economies are now implementing policies such as carbon emission taxes and technologically innovative production processes to reduce environmental pollution. Notably, this conclusion confirms the EKC theory, which is in line with the outcomes in Kızılgöl and Öndes (2022), Danish and Erdogan (2022), Ullah et al. (2022), and Yang et al. (2021b). However, the U-shaped behavior reported by Usman et al. (2020) and the N-shaped behavior reported by Danish (2019) conflict with this finding.

Third, we find that TI has a significant negative influence on ED in the OECD economies in our sample. A one percent increase in TI is associated with reductions in ED measured by EFI, ANS, and PN of 0.020%, 0.019%, and 0.080%, respectively. This suggests TI can be useful in reducing ED by slowing environmental pollution and improving environmental sustainability. This result indicates that TI helps to promote energy-efficient or energy-saving production processes in OECD countries, which has helped to

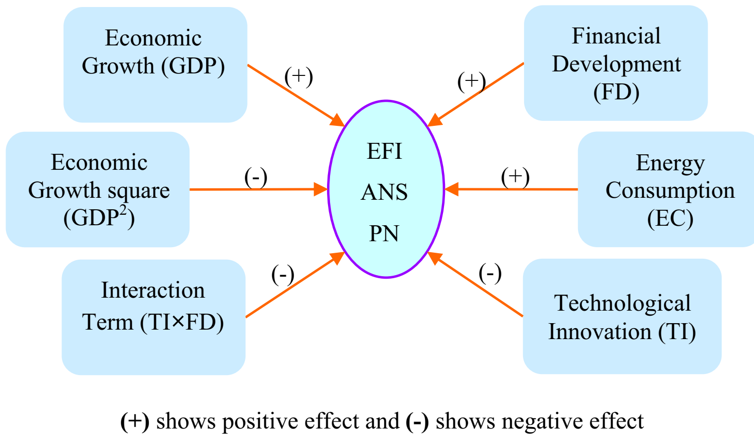


Fig. 5 Graphical design of estimation results for models 1, 5, and 6. *Source*: Provided by the authors

limit CO_2 emissions. This outcome is consistent with those reported by Adebayo et al. (2021) for Brazil, and by Ibrahim and Ajide (2021) for G20 countries; both of those studies find that TI has a positive role in reducing environmental pollution. However, this result contradicts the findings in Usman et al. (2020) and Wahab et al. (2021).

Fourth, our results show that FD reduces EQ. That is to say, EFI, ANS, and PN increase by 0.171%, 0.070%, and 0.024%, respectively, with every one percent increase in FD. This implies that FD not only increases ED but also decreases environmental sustainability in these OECD economies. One likely explanation for this result is that FD helps to promote business expansion, which increases EC, waste generation, and land use, and reduces EQ levels. This finding is consistent with those reported in Fakher et al. (2023) and Ibrahiem (2020); however, it is inconsistent with Saud et al. (2020) who find that FD has a negative effect on ED, and with Salahuddin and Gow (2019) who find that FD has an insignificant effect on environmental pollution.

Fifth, the coefficient of the interaction term TI-FD is negative and significant; hence, FD increases the negative impact of TI on ED. To be precise, a one percentage increase in this interaction term (TI-FD) decreases ED in the case of EFI, ANS, and PN by 0.178%, 0.062%, and 0.074%, respectively. Regarding these findings regarding the role of FD in changes in EFI, ANS, and PN through TI, overall an increasing impact is corroborated. Figure 5 illustrates the relationships between the dependent and independent variables.

The second part of this section explains the dynamic links between each of the economic variables using ESI and EPI as the dependent variables as shown in models 2 and 3, respectively, as these two indicators describe EQ rather than ED. As shown in Table 5, EC has a negative and statistically significant linkage with EQ as measured by ESI and EPI (models 2 and 3, respectively). EC has a positive linkage with ED and is a significant determinant of environmental pollution in the OECD countries in our sample. OECD countries are known for their rapid economic growth, which necessitates higher EC. The prolonged use of fossil fuels degrades EQ by increasing CO_2 emissions (Destek and Sinha 2020). This unfavorable impact of EC on EQ is mentioned in several other studies (Fakher et al. 2023, 2022; Pata 2021).

Additionally, the estimation results of models 2 and 3 with respect to the association between economic growth and EQ in terms of ESI and EPI reveal a negative coefficient for GDP growth and a positive coefficient for its square. This indicates that GDP growth has a negative effect on EQ in the early stages; however, after reaching a threshold, it reduces ED and helps to improve environmental quality. This outcome is consistent with EKC theory and aligns with Fakher and Inglesi-Lotz (2022) for OECD countries and contrasts with the U-shaped and inverted N-shaped relationships reported by Godil et al. (2020) and Fakher et al. (2023), respectively.

Table 5 also shows that TI increases ESI and EPI at the 1% significance level, implying that a one percent increase in TI increases ESI and EPI by 0.447% and 0.404%, as shown in models 2 and 3, respectively. Simply put, TI improves EQ as seen by the increases in ESI and EPI. This outcome shows that a high level of TI can mitigate environmental pollution, which is consistent with Ibrahim and Ajide (2021) and Acheampong (2019) who study 46 sub-Saharan African countries. However, it contradicts Chen and Lee (2020) who find that TI has an insignificant effect on EQ.

Based on the ESI and EPI models in Table 5, FD has a negative and significant linkage with EQ. A one percent increase in FD will result in 0.056% and 0.152% declines in EQ in models 2 and 3, respectively. This is likely due to the significant role FD can play in accelerating EC and waste generation by supporting business expansion, thus increasing ED. Our finding is consistent with Ibrahiem (2020) and Acheampong (2019) but contrasts with Charfeddine and Kahia (2019).

The coefficient of the interaction term TI-FD is positive; hence, FD supports the positive impact of TI on EQ, as presented in Figs. 6 and 7. However, this interactive effect is not statistically significant for ESI as seen in model 2. More precisely, a one percentage increase in this interaction term (TI-FD) will increase environmental sustainability by 0.022% based on ESI, and 0.069% based on EPI.

Finally, we examine the impacts of the independent variables on environmental pollution using EVI as the dependent variable, as shown in model 4. Here we start to analyze the behavior of the dependent variable in relation to EC. Energy use is considered to be the primary factor in escalating ED and the findings in our study confirm that EC has a

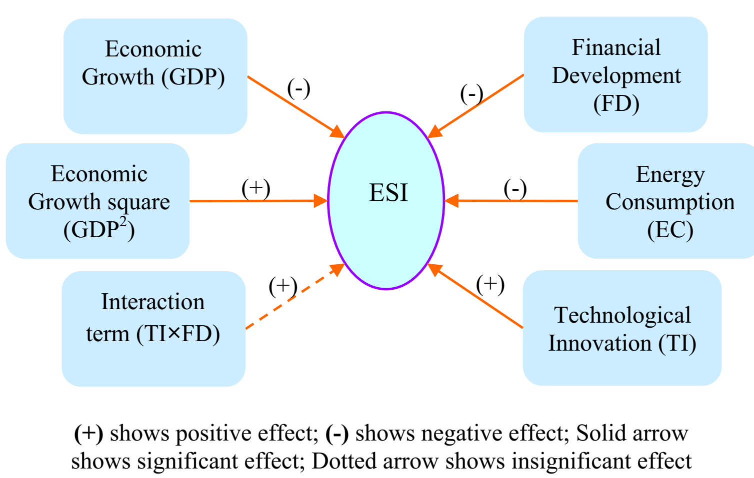
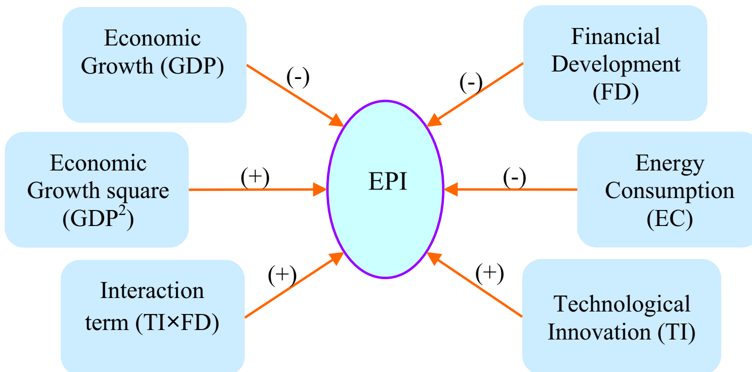


Fig. 6 Graphical design of estimation results for model 2. *Source*: Provided by the authors

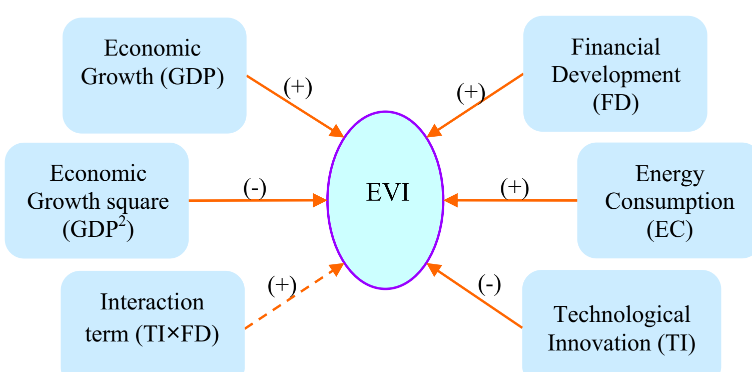


(+) shows positive effect and **(-)** shows negative effect

Fig. 7 Graphical design of estimation results for model 3. *Source*: Provided by the authors

mitigating (negative) effect on EQ. The results show that a one percent upsurge in EC causes a 0.010% rise in ED. This estimate is supported by several recent empirical studies, including Pata (2021) for the United States, and Destek and Sinha (2020) in the case of OECD countries.

Furthermore, our results verify the presence of an inverse U-patterned behavior between economic growth and EVI, thus supporting the EKC theory. The energy mix (largely fossil fuels) employed in the countries in this study can be blamed for the initial increase in ED. On the other side, the recent efforts made by these countries to pursue cleaner manufacturing methods using technical advancements create the inverted U-shape. This conclusion is supported by Anwar et al. (2021) but contradicts Rana and Sharma's (2019) inverted N-shaped EKC and Danish and Wang's (2019) N-shaped EKC. Our findings show that TI improves EQ by reducing EVI. More specifically, a one percent increase in TI is associated with a reduction in ED of 0.023%. Yang et al.'s (2021a) study of emerging market economies is consistent with this finding. However, this contrasts with the results in Chen and Lee (2020) and Samargandi (2017), who conclude that the effect of TI on EQ is insignificant.



(+) shows positive effect; **(-)** shows negative effect; Solid arrow shows significant effect; Dotted arrow shows insignificant effect

Fig. 8 Graphical design of estimation results for model 4. *Source*: Provided by the authors

We find that the coefficient of FD is positive and significant, implying that an increase in FD increases environmental vulnerability. This finding contradicts Nwani and Omoke (2020) who show that FD has a negative effect on ED, and Salahuddin and Gow (2019) who find that FD has an insignificant effect on ED. Finally, the coefficient of the interaction term is not statistically significant. Thus, we do not find a moderating impact of FD on EVI. Figure 8 illustrates these findings.

The results of diagnostic tests such as the second-order autocorrelation test and the Sargan test, confirm the accuracy and reliability of our results.

Conclusions and recommendations

Investigating the role of FD on the impact of TI on EQ using six indicators of EQ simultaneously provides useful information to policymakers for making decisions and formulating policies to progress toward a cleaner environment. This study investigates the moderating role of FD in the context of the nexus of TI and EQIs using the two-step Sys-GMM method on panel data from selected OECD countries from 2000 to 2019.

Our results show that the impact of EC on every environmental indicator increases ED. For each of the environmental indicators we use, FD is shown to be one of the meaningful and influential reasons for the reduction in EQ. Given the results from our models (models 1 to 6), we find support for the EKC theory based on economic growth and each of the EQIs. The favorable environmental effects of TI based on each of the EQIs suggest that an increase in TI increases environmental sustainability. The findings also show that FD supports the effect of TI on four of the environmental indicators but not for the environmental sustainability and environmental vulnerability indices, where the interaction term has no significant effect.

Our findings support the following policy suggestions. Favorable and efficient economic development can occur alongside environmental protections through policies that encourage and support TI in the production sector, supporting and improving FD for environmental technologies, making technologies more efficient, reducing the intensity of energy use, and increasing energy efficiency. Given the significant effect of FD and its effective role in the TI–EQ nexus, governments should view FD as an important contributor in designing policies for innovation. However, policies should also be designed to regulate FD as FD also enhances ED—only the interaction of FD with TI boosts EQ. Thus, restrictions on financing energy-intensive projects could discourage the expansion of dirty technologies that worsen environmental pollution. Finally, environmental considerations should also be addressed by adopting appropriate resource allocation policies to direct resources toward pro-environmental projects.

Although this research provides novel findings regarding the moderating impact of FD through TI in enhancing the quality of the environment, the focus of the research is only on selected OECD countries. Also, considering the nature of the data, the GMM-based analysis was conducted to explore the short-run dynamics. Notably, individual OECD countries belong to different income groups, which presents an important direction for future studies to explore long-run dynamics for specific income groups to help direct strategic innovation policies. Moreover, future studies could consider adding other important variables to the model, such as environmental technologies, environmental innovation, institutional variables, alternative energy investments, financial inclusion, and green finance, which could produce interesting results and support comprehensive environmental policies.

Appendix

See Table 6.

Table 6 Description of variables

Variables' name	Synoptic terms	Description	Data sources
Economic growth	GDP	GDP per capita in dollars at a 2010 fixed price	WDI
Energy consumption	EC	Energy consumption kilogram of crude oil equivalent per capita	WDI
Financial development	FD	Ratio of domestic credit provided for the private sector to GDP as a percentage of GDP	WDI
Technological innovation	TI	The aggregate number of residents and non-residents of patent applications	OECD.Stat
Ecological footprint index	EFI	The environmental degeneration condition is described by this index that is specified as the total fishing grounds, forestland, grazing land, crops land, built-up land, and carbon footprint expressed in global hectares (Gha) per person	GFN
Environmental performance index	EPI	The emphasis of this index is on two main goals that include proper management of the natural resources and preserving the environment (this goal is consisted of improving the ecosystem status and reducing environmental stress on the well-being of humans)	YCELP CIESIN
Adjusted net savings	ANS	Three various kinds of investment are included in this index which are human, natural capital, and physical investments. These investments are comprised of four constituents including carbon dioxide damage, ongoing education costs, resource rents (minerals, forests, and energy exhaustion), and net national saving	WDI
Pressures on nature	PN	Four crucial components are covered in this index including carbon dioxide-related damage and exhaustion of net forest, minerals, and energies	WDI
Environmental sustainability index	ESI	The capabilities of various nations for protecting the environment in upcoming years is assessed in this index. This index is extracted from 76 different statistical data sets that were represented by integrating 21 ESIs	YCELP CIESIN
Environmental vulnerability index	EVI	This index is comprised of five groups that include geological, natural services and resources, human population, geographical, and climatic variables. These variables show the environmental vulnerability of various countries	UNEP

WDI: World Development Indicators (databank.worldbank.org), OECD.Stat: OECD statistics (www.oecd-ilibrary.org); YCELP: Yale Center for Environmental Law and Policy (epi.envirocenter.yale.edu); CIESIN: Columbia University Center for International Earth Science Information Network (http://www.ciesin.org/); UNEP: United Nations Environment Programme (https://www.unep.org/); GFN: global footprint network (https://www.footprintnetwork.org/)

Abbreviations

FD	Financial Development
TI	Technological Innovation
EQIs	Environmental Quality Indicators
OECD	Organization for Economic Co-operation and Development
EFI	Ecological Footprint Index
ANS	Adjusted Net Saving
PN	Pressure on Nature
EPI	Environmental Performance Index
ESI	Environmental Sustainability Index
EVI	Environmental Vulnerability Index
EC	Energy Consumption
ED	Environmental Degradation
EQ	Environmental Quality
GMM	Generalized Method of Moments

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Declarations

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