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Modeling the impacts of technological innovation and financial development on environmental sustainability: New evidence from the world's top 14 financially developed countries

Assad Ullah [a], Mesut Dogan [b,*], Betul Altay Topcu [c], Haifa Saadaoui [d]

[a] School of Economics and Management, Hainan Normal University, China
[b] Bilecik Seyh Edebali University, Vocational School of Bozuyuk, Turkey
[c] Kayseri University, Vocational School of Social Sciences, Turkey
[d] University of Sfax, Faculty of Economics and Management of Sfax, Tunisia

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ABSTRACT

Developing a sustainable economic system in the wake of unprecedented environmental challenges is the major cry of the day. This study aims to investigate the impacts of financial development, technological innovation, globalization, trade openness, and renewable energy consumption on the ecological footprint of 14 countries with the highest levels of financial development. The utilized econometrics battery include slope homogeneity tests, Westerlund cointegration, panel Augmented Mean Group (AMG), and Dumitrescu-Hurlin (2012) causality approaches. The study period spans from 1990 to 2018. The empirical outcomes indicate that financial development negatively affects environmental sustainability. The results further reveal that globalization technological innovation, trade openness, and renewable energy consumption bolster environmental quality. Based on the causality outcomes, a bidirectional causal link is witnessed between technological innovation, globalization, renewable energy consumption, and ecological footprint; however, a unidirectional causality relationship exists from trade openness and financial development to ecological footprint. The study findings underscore the importance of globalization, technological innovation, trade openness, and renewable energy consumption in fine-tuning environmental policies and improving environmental quality in these countries.

1. Introduction

Environmental degradation is an issue that should not be put on the back burner, as it is a serious threat to our planet's well-being. The conference of the parties (COP) has extensively discussed the repercussions of failing to address numerous environmental problems, which have a negative impact on biodiversity and endanger human livelihood. In this respect, governments have emphasized that urgent actions are indispensable to reduce carbon emissions and reinstate degraded ecosystems. Water scarcity and increasing demand for energy and waste products in the world lead to environmental degradation [1,2]. Schumpeter (1934)argues that innovation and economic progress go in parallel. The prime advantage of technological innovation lies in the fact that it leads to eco-efficiency. Advanced technologies are not only cost-effective but come in handy in overcoming environmental challenges [3–7]. Technological innovation enhances environmental quality as and is undeniably one of the core elements of green economic expansion [8–12]. Of all the sustainable development goals (SDGs), the goal of realizing economic growth and simultaneously safeguarding the environment is at the core. Countries aiming to realize green growth can shift from dirty energy towards clean energy and can reduce carbon emissions to a considerable amount by exposing themselves to innovative technologies [13–17]. The theoretical foundation of this study predicates on the evidence that innovation leads to sustainability and financial development is the main driver of innovation, as financially developed countries not only attract foreign investment population but they encourage their local investors to opt for inbound investment; which have substantial spillovers over sustainability [18]. Since technological innovation and financial development could have both positive and negative spillovers over environmental sustainability, we

* Corresponding author.
E-mail addresses: assad@henu.edu.cn (A. Ullah), mesutdogan07@gmail.com (M. Dogan), altaytopcub@gmail.com (B.A. Topcu), Haifa.saadaoui@yahoo.fr (H. Saadaoui).

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attempt to discern whether the positive spillovers exhibit dominance over the negative spillovers,and the other way around.

The rising trend of greenhouse gas emissions is not merely detrimental to the ecosystem, it has also a severe impact on society. As a result, combating environmental degradation (ED) in recent years has been extremely essential for both developed and developing countries [19]. Nevertheless, researchers investigate the determinants of environmental quality (EQ) for the objective of sustainable development to reduce the ecological footprint (EF) and make recommendations regarding the improvement of EQ on a global scale [20]. In recent studies in the literature, variables such as trade openness (TO), globalization (GLO), renewable energy consumption (RE), technological innovation (TI), and financial development (FD) are among the major determinants of EQ [21–24] ; [25–27]. Environmentally friendly technologies utilize energy efficiently which not only results in low carbon emissions but also propels green growth [28,29].

The majority of the studies conducted on the determinants of EQ, are based on the Environmental Kuznets Curve (EKC) hypothesis. According to this hypothesis, during the first phase of economic expansion, ED rises depending on the expansion in economic level, and declines after exceeding a particular income level [30]. In this vein [31], categorized the impacts of TO or economic activity on ED into three groups such as; scale effect, composition effect, and technological effect. The scale effect explains the increase in ED caused by the economic activities conducted with the use of fossil fuels due to the rise in commercial activities in the period during which the national economies begin to grow. However, due to the changes in the trade policies of the countries in the following phases of growth, ED decreases due to the specialization in certain areas with lower pollution levels (composition effect), the development of technology, and the increasing competitive advantage (technology effect) [32].

TI may help the improvement of EQ by increasing productivity and development in the economy [24,33,34]. TI can help reduce the EF by providing efficient management and use of natural resources [27]. By boosting natural resources, technological improvements can minimize CO2 emissions (Adebayo et al., 2023). TI in the energy sector plays a crucial role in the transition from dirty energy use to cleaner energy resources [35,36]. Subsequently, TI is one of the most important means of reducing ED, and at the same time, enhancing economic growth [25,27,37–39]. However, in some circumstances, TI has an adverse impact on ED [40,41]. For instance, due to insufficient R&D investments, TI may be directed to non-environmentally-friendly areas, resulting a deterioration of EQ [42,43].). Although new technologies improve resource usage, they also generate new waste streams and pollutants, which degrade the environment [44]. In fact, some innovative technologies in the fossil fuel industry enhance enviromental degradation [45].

FD is among the important determinants of EQ [46]. In fact [47,48], were the first to study the interaction between the environment and FD. [48] stated that financial institutions ignored environmental problems by encouraging short-term loans. Similarly [47], drew attention to the role of multilateral banks in improving EQ. The authors considered that the financial aid mechanism added by the World Bank generally neglected environmental aspects upon the provision of funding. On the other hand, a sound financial market assists economic agents in accessing capital, and thus, stimulates economic activity. Easier access to financial resources raises demand for energy use, and therefore, ED is exacerbated [49]. Nonetheless, some studies suggested that FD could improve EQ. A well-developed financial system encourages the use of better and environmental-friendly technologies [50].

Advanced technological services and energy consumption can be utilized more efficiently in a developed financial sector. Therefore, environmental safety regulations may be supported with minimum cost and maximum funds [51]. Also, a developed financial sector contributes to increasing economic growth and development. This helps investors and consumers to increase confidence in business expansion by mitigating investment barriers and the effort for financial resources [52]. The main objective of this study is to investigate the determinants of ecological footprint in the world's top 14 financial development countries. To be specific, this paper is interested in the influences of FD, TI, GLO, TO, and RE on the environment sustainability. The annual data of 14 countries are at the top rank in the IMF's FD index over the period 1990–2018. To test the stationarity features of the variables included in the analysis, the "CADF" and "CIPS" unit root tests are performed. Besides, the long-term relationships between the series are considered by Ref. [53] Panel LM bootstrap cointegration test. Thus, the AMG estimator and the [54] test are used to examine long-term and causal associations, respectively.

One of the prime challenges for the government in this modern era is to strike a balance between economic development and environmental sustainability. In the extant literature, one strand of research probed the nexus between technological innovation and carbon emission [18]; Ali et al., 2023; [55–57]. Another strand determined the linkage between technological innovation and green growth [8,58–60]. It is still a debatable issue whether innovation promotes or demotes carbon emission. Technological innovation mitigates dirty energy concerns, promotes clean energy projects and improves environment [3,61]. Alternative studies confirmed that innovation propels carbon emission (Du, Li, & Yan, 2019). Studying the relationship between technological advancement and environmental quality in G20 nations, Erdogan et al., 2020), established that the relationship between the two is not necessarily persistent. In the similar manner, studies also determined the effect of financial development of environmental quality [62–65]. The prime aim of this research work is to probe whether both financial innovation and technological innovation affect environmental sustainability in the top 14 financially developed countries (United States, United Kingdom, Germany, France, Sweden, Switzerland, Netherlands, Norway, Denmark, Japan, Republic of Korea, Portugal, Spain, and Thailand). The main motivation behind selecting these countries lies in the fact that the ace 14 financially developed countries are well-equipped to augment technology, while at same time financial development often exhibit dual nature pertaining to environmental sustainability. For instance, banking-based financial soundness bolster carbon emission, whereas, market (stock) based financial development assist in mitigating carbon emission or improve environmental quality. In this respect, exploring the nexus between technological innovation and financial development will on environmental sustainability will highlight if the former two promotes environmental quality in financially sound countries.

Our study contributes to the current literature in two aspects: i) few research have looked into the connection between innovation technology and ecological footprint. The impact of technical advancement on environmental sustainability can yield vital advice for dealing with today's environmental issues. Indeed, based on past research, the connections studied between variables are relatively limited. In fact, Identifying the association between FD, TI, GLO, TO, RE, and EF based on the countries with the greatest level of FD allows policymakers to develop more realistic and precise environmental protection measures. ii) besides, there is no actual research in the literature on the countries with the highest level of FD in terms of the aforementioned variables. We think that relating the capacity of countries with highly developed financial sectors and significant technology investments to the ecological footprint is an important question. In fact, this study will provide answers to concerns about advanced nations' performance in allocating financial resources to development goals as specified in the context of both the Paris Agreement and the 2030 Agenda for sustainable development. The puzzle of whether financial development and technological advancement support environmental sustainability in financially sound countries necessitates is still not resolved to the satisfaction of the curious mind and further necessitates a multifaceted approach. Examining the combined effect of technological progress and financial development on environmental sustainability in financially sound counties will provide policymakers with insights to devise pragmatic strategies to cope with environmental challeges and attain sustainable economic growth. Put differently, the findings of this research work will extend our understanding of the interplay among technology, finance, and the environment but will offer stakeholders and policymakers valuable insights to understand the nuances of sustainable development.

Subsequent to the introduction part of the study, the second part of the study presents literature reviews. The model and methodology along with the dataset of the study are introduced in the third part, and the obtained empirical findings are included in the fourth part. In the last part the study is concluded and recommendations are made for potential investors and policymakers, and explanations regarding the direction of future studies are presented.

2. Literature review

The intensity of the environmental discussion has generated an abundance of research into the factors explaining environmental sustainability. To this end, our review of the existing empirical literature reveals inconclusive outcomes. A detailed review of the connections between financial development, technological innovation, globalization, trade, renewable energy, and environmental quality is analyzed in this section.

2.1. Nexus between financial development and environmental quality

With an increased interest in funding environmental sustainability, a rising corpus of research has investigated the influence of financial development on environmental quality. In fact, financial development can adversely affect the environment quality. The literature points out that in the case of a developed financial market, financial institutions can meet the financial needs of individuals. Easy access to finance resources leads to an increase in demand and subsequently in society's purchasing power, which can have negative consequences for the environment, especially as resource consumption increases.

In this sens [52], found that FD led to ED by increasing the EF in 59 BRI countries [36]. investigated the connections between EF, population density, GLO, income, energy consumption, and FD in Japan. They detected that FD positively affect EF. Similarly [24], stated that the increase in FD for Western Asian and Middle Eastern countries deteriorated EQ [20]. concluded that the increase in FD in selected BRI countries over the period 1990–2014 increased the EF. [66–69]; and [60] identified a positive relationship between FD and ED.

On the other hand, a developed financial system can participate in environmental protection through credits granted to green projects. In fact, financial system can facilitate investment in renewable energy projects by easing the lending process [70]. Furthermore, the literature shows that increasing the FD leads to a decline in information asymmetries, an improvement in R&D, and the transfer of technological advancements to the energy sector, hence improving QE.

For instance, [71]; in their study conducted for 93 countries by income levels, found that FD reduced ED in all countries except for the low-income group [72]. investigated the relationship between FD and ED variables (EF and CO_2 emissions) for 131 countries and found that FD reduced ED. Using a case study of various OPEC countries [73], demonstrate that FD promotes environmental sustainability by acting as a moderator to the negative effect of economic expansion on environmental quality [74,75]. found a negative relationship between carbon emissions and financial development for OECD countries.

Other investigations akin to this finding, [76,77]; and [78] found that FD contributed to reducing the EF of 27 countries; Malaysia; and OECD countries, respectively. [51,79–82]; and [21] argued that FD led to an improvement of EQ in the BRIC countries, 24 transition economies, Indonesia, the GCC countries, Pakistan, and 184 countries, respectively.

2.2. Nexus between globalization and environmental quality

Upon examining the literature on the GLO and EF nexus, it is seen that the environmental impacts of GLO are mixed. According to recent studies, the GLO improves the accessibility and affordability of products and services, which is likely to boost the consumption of fossil fuels and create environmental damage. For instance, Kırıkkaleli et al. (2021) found that GLO promoted ED by increasing the level of Turkey's EF [20]. found that the EF for belt-one-road initiative (BRI) countries increased due to the widespread of GLO. Similarly, in their study of South Asian economies, Sabir and Görüs (2019) found that GLO caused ED [83]. revealed that GLO in MENA economies degraded the environment. In contrast, they detected no evidence of a significant link between GLO and EF in non-petroleum-exporting countries among MENA economies. Apart from these studies, [72,84–88]; and [36] found the negative impacts of GLO on EQ in India; Malaysia; Japan; BRICS economies; ASEAN countries; 155 countries; and Japan, respectively. Another conclusion derived from the empirical studies is that GLO introduced new technologies and promoted innovation by removing trade restrictions. Furthermore, by implementing resource reallocation and the deployment of energy-efficient technology, GLO can reduce the consumption of fossil energy resources and therefore improve EQ.

The second of the empirical findings on the link between GLO and EF is about the impacts of GLO on the improvement of EQ. For instance, Danish et al. (2020) investigated the link between financial GLO and EF in the context of developing countries and detected that financial GLO increased EQ by reducing EF [89]. found that GLO was beneficial for reducing EF levels in Egypt. Similarly [27], found that GLO reduced the EF only in African and Latin American countries among 73 developing countries over the period 1990–2016. Also, [65,90–92]; and [93] found similar results for SSA regions; APEC countries; OECD countries; 16 CEE countries; and UAE countries, respectively.

2.3. Nexus between renewable energy and environmental quality

Global warming and ED have become the most important global problems by aggravating the destruction of ecosystems (Usman, Akadiri, and Adeshola 2020). In various studies, the most important reason for ED was detected as the rise in greenhouse gas emissions due to excessive consumption of non-renewable resources (Apergis and Öztürk 2015 [12]; Mesagan et al., 2018; [91,94,95]. In this context, the use of renewable energy and its connection with the environment has been at the focal point of recent discussions.

Negative relationships were identified in a significant portion of the studies conducted regarding the impact of RE on ED. For instance, Ref. [96], found that RE reduced the EF in 8 developing Asian countries. In their study [97], indicated that the use of RE reduced the EF and increased the EQ by utilizing the data of developing countries over the period 1990–2016 [98]. found that RE had a positive impact on the EF for 58 developed and developing countries over the period 1980–2009 [99]. confirm clean energy's impact in reducing EF in 29 OECD nations [100]. investigate the impact of renewable energy consumption on environmental sustainability for a panel of nations from the Organization of Petroleum Exporting Nations from 1994 to 2019. They demonstrate the importance of renewable energies in promoting environmental sustainability.

Similarly, [101–104] and [105] suggested that clean energy consumption improved environmental sustainability. Nevertheless, Cakmak and Acar (2022) found that RE did not affect the EF of petroleum-producing economies such as the USA, Russia, Saudi Arabia, Canada, China, Brazil, Kuwait, and Nigeria over the period 1999–2017.

2.4. Nexus between trade openness and environmental quality

The rise in worldwide GLO trends has made significant contributions to the liberalization of trade among countries. The liberalization of trade has led to various studies being conducted regarding the impact of TO on the EQ [106,107]. TO has a real influence on the EF through various channels. The level of development and industrialization of a country determines the direction of such specific effect [108]. Advanced technologies can be brought into environmentally friendly production processes in developed countries. In the initial phase of development, policymakers of any country have been more concerned about promoting growth rather than maintaining a clean environment [109]. Subsequently, these countries can import cheap and highly pollutant technologies to enhance production. The technical effect of TO during this cycle may lead to deterioration in EQ [108–110].

In this direction [98], revealed that TO increased the EF of 58 countries over the period 1980–2009 [111]. showed that TO reduces EQ in European countries. Similarly [112], found that TO increased EF in their study utilizing the data of the Nigerian economy over the period 1970–2017. On the other hand [113], found that TO enhance the EQ in 144 countries over the period 1988–2008. Moreover, Kırıkkaleli et al. (2021) argued that TO reduced the EF in the short term and that policies promoting RE should have been adopted to improve EQ in the Turkish sample. Using an asymmetric analysis, Omri and Saadaoui (2022) demonstrated that in the long run, only a negative change can contribute to reducing EQ in the case of France. These conclusions are also confirmed by Refs. [114–116]; and [109].

2.5. Nexus between technological innovation and environmental quality

Existing literature indicates that TI has a significant influence on environmental sustainability. Mixed results have been obtained depending on the employed methods, sampling, and the period considered in the research studies conducted on the relationship between TI and EQ. Nevertheless, a significant part of empirical research studies determined that TI contributed to EQ. For instance Refs. [117,118], found that TI would have improved EQ for Pakistan and the EU countries, respectively. The authors associated their findings from these studies with increases in RE usage and advanced technology reducing the use of fossil-based energy resources. Besides, in some studies [119,120] it was stated that technological innovations could have enabled the development of environmental technologies that minimized the detriment of waste to the environment.

[121] revealed that TI improved EQ by reducing ED in the Chinese sample. They found a U-shaped relationship between TI and EF [122]. detected that a stable and long-term relationship existed between TI and EF. Similarly [123], concluded that TI was a prerequisite for reducing the EF in developing economies. Similar findings were detected by Refs. [3,6,19,24,25,97,124,125]. Unlike these results [32], found that TI did not have a significant impact on the EF for large emerging market countries. Similarly [126], revealed that TI did not affect the EF of South Asian countries. On the other hand [127], concluded that TI significantly impaired EQ in the case of APEC countries.

The empirical literature described above concentrated on the determinants of environmental quality. It revealed the environmental implications of financial development, technological innovation, globalization, trade openness, and renewable energies. Despite, the rising number of research on this subject, there is still little agreement on the conclusions reached. This can be related to the empirical methodologies used, the contexts analyzed, and the dispersion of environmental sustainability indices. The potential innovations of this study to address this gap and contribute to the expanding literature are as follows. First, this study aims to invest in a broader variety of environmental sustainability determinants by addressing the critical role of technological innovation and financial development. Second, the study focuses on the world's most developed countries in terms of financial development, looking into the capabilities of top-ranked institutions and banks to contribute to environmental decarbonization.

3. Data and methodological framework

In this study, the environmental quality indicator was measured by the ecological footprint [73,128]. developed a composite environmental quality index based on six environmental indicators. This study analyzes the mediating role of TO and TI on EF as the determinants of EQ. In the study, the data of 14[1] countries obtained over the period 1990–2018, which rank first place in the FD index in the IMF database as of 2020, are used. These countries are included in Fig. 1.

In this study, explanatory variables such as FD, GLO, and RE are included in the EF model, as well as TO and TI. Theoretically, FD can affect EQ positively as well as negatively. A developed financial structure of a country can reduce financial costs. However, the reduction in financial costs may lead to ED by increasing investment in new production areas. On the other hand, channeling these investments into green and environmentally friendly investments and renewable energy sources will improve the EQ [129].

The impact of GLO on the environment can also be positive or negative. GLO increases fossil fuel consumption by facilitating accessibility to products and services, and this situation harms the environment. In other words, GLO can cause ED by promoting economic growth, trade, and investment. According to the environmental perspective of GLO; multinational companies, by their nature, act by the environmental policies of the countries in which they operate and take measures to protect the environment as a company [66]; Kırıkkaleli et al., 2021).

The environmental damage caused by global warming and the increase in fossil fuel consumption in the world has led to an increasing demand for renewable energy sources. Therefore, clean energy sources should be encouraged instead of fossil fuels to improve EQ. Therefore, the most important source in reducing EQ is renewable energy sources [130].

On the other hand, the theoretical connections between trade and the environment are explained with technological, scale, and compositional effects. Increasing trade volume according to the technological effect reduces ED through the transfer of both goods and information. On the other hand, the scale effect means that more production deteriorates EQ as it leads to increased trade relations between countries. Finally, the compositional effect adopts the view that the productions in which most of the less developed countries are exposed to pollution cause ED. Thus, only the technological impact contributes to the improvement of EQ [131,132].

The theoretical connection between TI and the environment is related to the consequences of innovation in favor of the environment. Namely, TI improves environmental quality by reducing the use of fossil-based energy sources [117,118]. In addition, TI can enable the development of environmental technologies that will minimize the damage caused by waste to the environment [9,119].

Thus, alongside the theoretical literature, by following the empirical studies such as [3,24,27]; and [133] the logarithmic regression model is used to predict the aforementioned relationships:

$$ln\ EF_{i,t} = \beta_0 + \beta_1\ ln\ TI_{i,t} + \beta_2 lnFD_{i,t} + \beta_3\ ln\ GLO_{i,t} + \beta_4\ ln\ TO_{i,t} + \beta_4\ ln\ RE_{i,t} + \varepsilon_{i,t} \quad (1)$$

In Equation (1), $i = 1, \ldots, N$ indicates cross-section units, $t = 1, \ldots, T$ denotes time, ε_{it} represents error terms. $\beta_1, \ldots\ldots, \beta_4$ denote the parameters that quantify the influence of EF's explanatory series. The variables used in the study, the definitions of the variables, their sources, and studies using the variables are presented in Table 1.

[1] Switzerland, Japan, United States, United Kingdom, Korea Rep., Spain, France, Germany, Thailand, Sweden, Netherlands, Norway, Denmark, Portugal. Source: IMF, Financial Development Index Database, https://data.imf.org/?sk=F8032E80-B36C-43B1-AC26-493C5B1CD33B&sId=1481207801912.

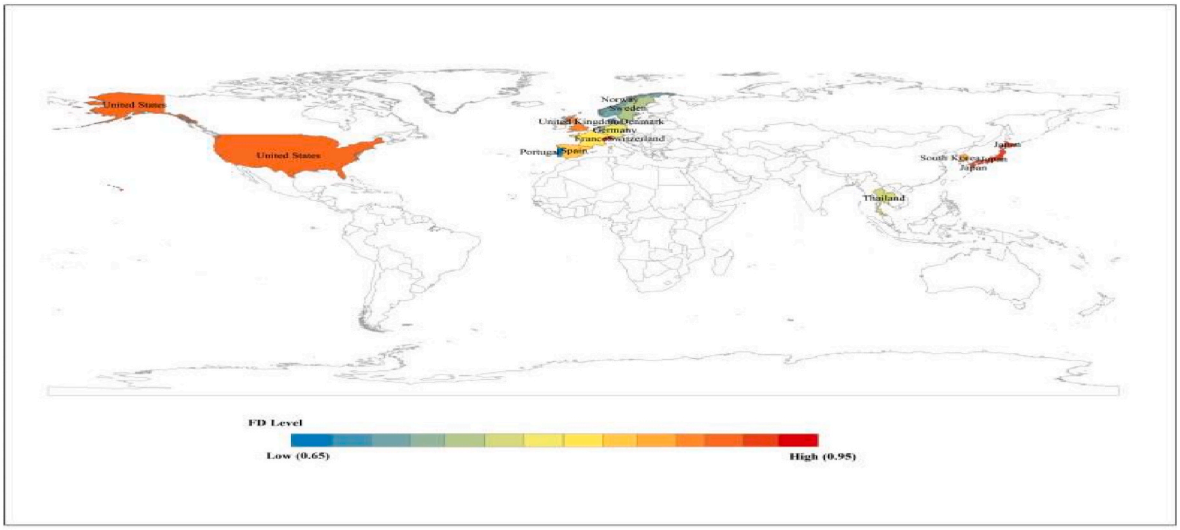

Fig. 1. Countries used in the study.

Table 1
Variables, descriptions, sources, and studies using the variables.

Variables	Descriptions	Sources	Studies using the variables
EF	The ecological footprint (global hectares per capita)	Global Footprint Network	[36,52,134]
TI	Patent applications, nonresidents	World Bank-WDI	[24,135,136]
FD	Financial development index	IMF Databank	Altay Topcu and Doğan (2022) [137–139];
GLO	Globalization index	KOF Swiss Economic Institute	[65,92]
TO	Trade (% of GDP)	World Bank-WDI	[107,116]
RE	Renewable energy consumption (% of total final energy consumption)	World Bank-WDI	[132,133,140]

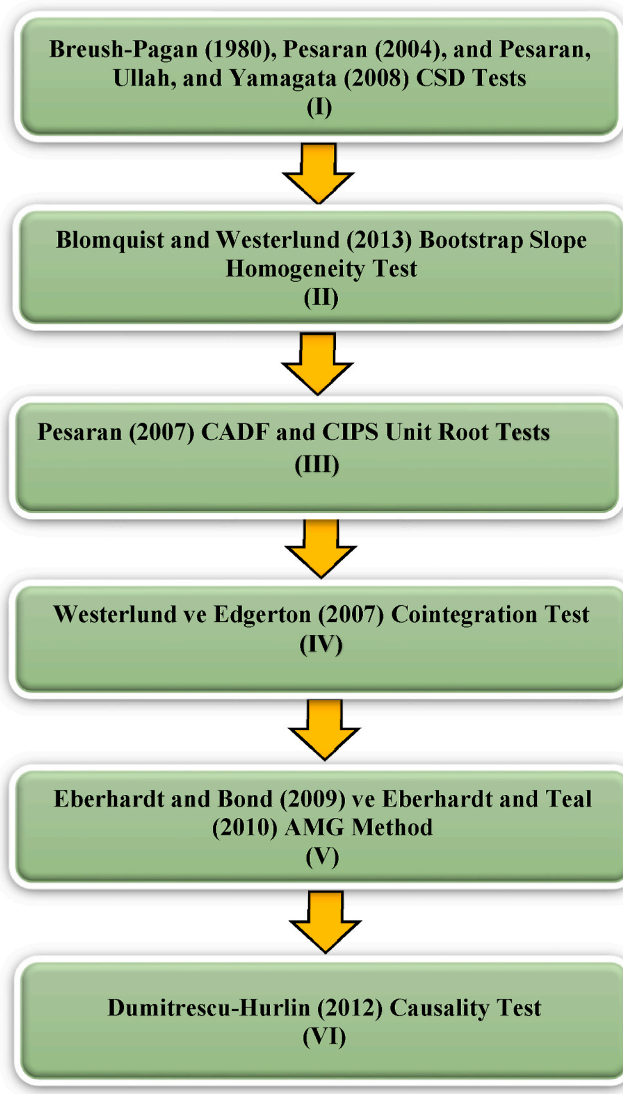

Fig. 2. The methodological framework of the study.

This study focuses on the effects of TO and TI on EF. A six-stage panel data strategy is preferred in the study. Fig. 2 illustrates this strategy. Accordingly, in the first stage of this study, the cross-section dependence-CSD (I) and in the second stage the slope homogeneity (II) are examined. In the third stage of the study, according to the previous results, second-generation unit root tests (III) and in the fourth stage cointegration test (IV) are applied. In the fifth stage, AMG estimation (V) is made by the panel data set. Finally, in the sixth stage, the causality relationship (VI) is estimated.

Some researchers argue that CSD needs to be considered in panel data evaluations and that the results obtained in analyses without it would be biased and inconsistent [141–143]. In this research, to control the CSD series problem, the Breush-Pagan LM test developed by Ref. [144]; Pesaran scaled LM (CD_{LM}) and Pesaran CD test developed by Ref. [141]; and the Bias-Corrected Scaled LM (LM_{adj}) test initiated by Ref. [145] is performed. These four tests are expressed as shown in Equations (2)–(5), respectively:

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}^{2} \tag{2}$$

$$CD_{LM} = \sqrt{\frac{1}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\left(T\widehat{\rho}_{ij}^{2}-1\right) \tag{3}$$

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=1+1}^{N}\widehat{\rho}_{ij}\right) \tag{4}$$

$$LM_{adj} = \left(\frac{2}{N(N-1)}\right)^{1/2}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\widehat{\rho}_{ij}^{2}(T-K-1)\frac{\widehat{\rho}_{ij}-\widehat{\mu}_{Tij}}{\upsilon_{Tij}} \sim N(0,1) \tag{5}$$

In the tests shown in Equations (2)–(5); rejecting the H_0 hypothesis and accepting the H_1 hypothesis indicates the existence of a cross-sectional dependence among the series [146].

Following the analyses of the CSD, it is determined whether or not slope homogeneity occurs. The presence of heterogeneous slope coefficients is identified by Ref. [147] tests, which were later evaluated by Ref. [148]. Nonetheless, if heteroskedasticity and serial correlation are found in regression errors [149], tests are used.

The following equations provide the HAC version of the homogeneity test based on the [149] delta test.

$$\Delta_{HAC} = \sqrt{N}\left(\frac{N^{-1}S_{HAC}-k}{\sqrt{2k}}\right) \tag{6}$$

$$S_{HAC} = \sum_{i=1}^{N} T(\widehat{\beta}_i - \widehat{\beta})'\left(\widehat{O}_{iT}V_{iT}^{-1}\widehat{O}_{iT}\right)(\widehat{\beta}_i - \widehat{\beta}) \tag{7}$$

$$\widehat{\beta} = \left(\sum_{i=1}^{N} T\widehat{O}_{iT}V_{iT}^{-1}\widehat{O}_{iT}\right)^{-1}\sum_{i=1}^{N}\widehat{O}_{iT}\widehat{V}_{iT}^{-1}X_i'M_T y_i \tag{8}$$

It is stated that the slope coefficients are heterogeneous in Equations (6)–(8) if the H_0 hypothesis is rejected and the H_1 the hypothesis is accepted. According to Ref. [132]; if a CSD problem exists among the series and the slope coefficients are heterogeneous, the second-generation unit root tests should be preferred. The second-generation tests alleviate the CSD problem and produce more reliable findings from heterogeneous panels. Given the presence of CSD and slope heterogeneity in the study [150], cross-sectional ADF (CADF) and cross-sectional augmented IPS (CIPS) panel unit root tests are recommended [150]. CADF unit root test is as shown in Equations (9) and (10):

$$\Delta y_{it} = \alpha_i + \beta_i y_{i,t-1} + u_{it} \tag{9}$$

$$u_{it} = \gamma f_t + \varepsilon_{it} \tag{10}$$

f_t in Equation (10) represented the unobservable indicators. f_t is considered to be stationary. In this statistical test, the cross-sectional dependence in the model relies on unobserved factors, and $\Delta\overline{y}_{it}$ and $\overline{y}_{i,t-1}$, which captures the cross-sectional means, is contained in the equation instead of the unobservable common component. The CADF test is as follows in the absence of autocorrelation in the error term or factor:

$$\Delta y_{it} = \alpha_i + \rho_i y_{i,t-1} + d_0\overline{y}_{t-1} + d_1\Delta\overline{y}_t + \varepsilon_{it} \tag{11}$$

$\overline{y}$ Equation (11) shows the average value of all observations over time.

When autocorrelation is identified in the error term or factor, the equation can be enlarged as demonstrated in Equation (12) by incorporating the first-order differences of y_{it} and $\overline{y}_{it}$:

$$\Delta y_{i,t} = \alpha_i + \rho_i y_{i,t-1} + c_i\overline{y}_{t-1} + \sum\nolimits_{j=0}^{p} d_{i,j}\Delta\overline{y}_{t-j} + \sum\nolimits_{j=0}^{p}\beta_{i,j}\Delta y_{i,t-j} + \mu_{i,t} \tag{12}$$

After determining the CADF regression, the mean values of t-statistics of the lagged factors are used to construct the CIPS statistic in Equation (13):

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \tag{13}$$

[91] argued that it was not appropriate to perform traditional cointegration tests if the CSD existed among variables. Thus [53], the Panel LM bootstrap cointegration test is preferred in this study. The CSD and slope heterogeneity are taken into account in Ref. [53] cointegration technique, which is derived from the Lagrange multiplier test suggested by Ref. [151]. It is also seen that it yields better results in small samples. According to this test, the acceptance of the H_0 hypothesis indicates that cointegration relationships exist among the variables. The panel cointegration equation of [53] is expressed as shown in Equations (14) and (15):

$$\gamma_{it} = \alpha_i + x_{it}'\beta_{it} + Z_{it} \tag{14}$$

$$Z_{it} = \mu_{it} + V_{it}\ V_{it} = \sum\nolimits_{J=1}^{t}\eta_{ij} \tag{15}$$

In Equation (15); t shows the time variable, i denotes the cross-section unit, and Z_{it} represents the error term. The LM statistic in which [53] test for cointegration is performed for the entire panel using LM test bootstrap critical values in the presence of the cross-section dependence is shown in Equation (16):

$$LM_N^{+} = \frac{1}{NT^2}\sum_{i=1}^{N}\sum_{t=1}^{t}\widehat{\omega}_i^{-2}S_{it}^{2} \tag{16}$$

In Equation (16), S_{it}^2 denotes the partial sum of the error term (Z_{it}), and $\widehat{\omega}_i^{-2}$ stands for the long-run variance of μ_{it}.

Subsequent to the finding of long-run cointegrating relationships among the variables, the long-term elasticity coefficients are predicted by employing the AMG method. Although the first-generation estimators such as the Mean Group Estimator (MG) and the Pooled Mean Group Estimator (PMG) in panel analyses provide for heterogeneity, they are not CSD-resistant estimators [152,153]. Therefore, one of the most appropriate estimation methods in the case of the CSD and slope heterogeneity in panel data is the AMG estimator developed by Refs. [154,155]. [156] asserted that if the variables had the CSD and slope heterogeneity existed among the cross-sectional units, the panel estimates might have caused biased and inconsistent results. To overcome these problems, the AMG estimation technique, which has significant advantages over classical estimators, is suggested. Another feature of the AMG estimation technique is that it may contribute to the presentation of policy recommendations by making country-specific estimations in the panel.

The AMG method is based on a two-stage process [132,154]. The process in the first stage is as shown in Equation (17):

$$\Delta X_{it} = \delta_i + \beta_i\Delta Y_{it} + \gamma_i A_t + \sum_{t=2}^{T}\delta_i\Delta D_t + \varepsilon_{it} \tag{17}$$

In the first phase shown in Equation (17), the model is estimated by taking the first differences of the variables since non-stationary variables and unobservable factors yield biased results in the regression model established with the values of the variables at the level. The model estimated in the second phase is as shown in Equation (18):

$$\widehat{\beta}_{AMG} = N^{-1}\sum_{i=1}^{N}\widehat{\beta}_i \tag{18}$$

In the second phase shown in Equation (18), the time dummy variable is included in the regression for each cross-sectional unit. A linear trend term is also included in the regression. The AMG estimates are obtained by taking the average values of individual country estimates.

The panel causality test, introduced by Dumitrescu-Hurlin (2012), is carried out in the final stage of this empirical study. This test provides the advantage of producing effective results in heterogeneous panels where cross-sectional dependency is identified. Furthermore, it can produce estimates in every case, whether or not there is a cointegrating link.

The following equation represents the basic regression:

$$y_{i,t} = \alpha_i + \sum_{k=1}^{K} \beta_{ik} y_{i,t-k} + \sum_{k=1}^{K} \gamma_{i,k} X_{i,t-k} + \varepsilon_{it} \quad (19)$$

In Equation (19), $X_{i,t}$ and $y_{i,t}$ show the observations related to the stationary variable in the period t for all i. The coefficients are supposed to differ for each i and to be invariant across time. It is presumed that the lag length for each i is the same and that the panel is balanced.

Then, the H_0 hypothesis means that there is no causality, however the alternative hypothesis H_1 states that there exists a causality link between variables.

4. Empirical findings

In this part, firstly, the summary statistics of the variables included in the analysis and the correlation matrix are presented. Secondly, the CSD test and [149] slope homogeneity test results are given for each of the variables. Then, Pesaran's (2007) CADF, and CIPS panel stationarity tests, as well as [53] cointegration test is included. Lastly, the long-term AMG estimation and Dumitrescu and Hurlin's (D-H) causality test results are assessed.

4.1. Summary statistics and correlation analysis results

The summary statistics and correlation matrix of the panel data of 14 countries with FD level having 406 observation values over the period 1990–2018 are presented in Table 2. TI is the first variable with a mean value of 7.771. The variable with the lowest mean value (−0.359) is FD. TI has the highest median value (7.553). The variable with the lowest median value (−0.317) is FD. Upon considering the maximum values, the variable with the highest value (12.730) is TI, whereas the variable with the lowest value (0.000) is FD. The variable with the lowest value (−2.799) is EF, and the variable with the highest value (3.782) is GLO. The variable with the highest standard deviation (2.342) is TI, whereas the lowest standard deviation (0.123) belongs to GLO. The variable with the highest skewness value (0.395) is TO, and the variable with the lowest skewness value (−1.710) is EF. Furthermore, the variable with the highest kurtosis value (6.322) is GLO, whereas the variable with the lowest kurtosis value (2.197) is TI.

The correlation of the sample presented in Table 2 in terms of the predicted model; GLO, TO, and RE have a positive correlation with EF.

Table 2
Summary statistics and correlation matrix.

	lnEF	lnTI	lnFD	lnGLO	lnTO	lnRE
Mean	1.284	7.771	−0.359	4.358	4.330	2.232
Median	1.712	7.553	−0.317	4.393	4.226	2.349
Max.	2.875	12.730	0.000	4.507	6.080	4.117
Min.	−2.799	2.890	−1.099	3.782	2.760	−0.817
Std. dev.	1.290	2.342	0.221	0.123	0.754	1.207
Skewness	−1.710	0.291	−0.972	−1.700	0.395	−0.493
Kurtosis	4.752	2.197	3.697	6.322	2.847	2.478
Obs.	406	406	406	406	406	406
lnEI	1.000					
t-Statistic	–					
lnTI	−0.268*	1.000				
t-Statistic	−5.599	–				
lnFD	−0.045	0.175*	1.000			
t-Statistic	−0.923	3.585	–			
lnGLO	0.302*	−0.313*	0.560*	1.000		
t-Statistic	6.368	−6.630	13.588	–		
lnTO	0.156*	−0.545*	−0.008	0.262*	1.000	
t-Statistic	3.186	−13.092	−0.167	5.464	–	
lnRE	0.562*	−0.513*	0.005	0.280*	0.270*	1.000
t-Statistic	13.661	−12.037	0.115	5.881	5.650	–

Note: * indicates significance at %1 level.

However, TI and FD have a negative correlation with EF. The correlation matrix also includes some other important correlation results among the series.

4.2. CSD and slope homogeneity test results

The cross-sectional dependence test findings for the model are presented in Table 3. As demonstrated in Table 3, the results of the LM and CD tests indicate that the H_0 hypothesis, which predicts no CSD for all series, is rejected, indicating the presence of CSD. This outcome implies that shocks occurring in one of the 14 nations studied are likely to spread to other countries.

Table 4 shows the results of the delta tests established by Ref. [149] to assess the existence of slope homogeneity.

The results reveal that the H_0 hypothesis, which requires the existence of slope homogeneity, is rejected, showing that. slope heterogeneity exists for the aforementioned model. This outcome can be interpreted as the model with heterogeneous panel data.

4.3. Unit root and cointegration test results

In the next phase of the study, the stationarity of the series for 14 countries with FD level is investigated by performing the second generation panel unit root tests such as CSD [150], CADF, and CIPS tests. Panel unit root tests are estimated for the fixed model. Test results are presented in Table 5. Based on CADF and CIPS test outcomes; EF, FD, GLO, and RE variables are stationary both at the level and at the first difference. TI and TO variables become stationary at the first difference.

Westerlund-Edgerton's LM Bootstrap Cointegration test results are presented in Table 6. Since CSD exists among the series, the Bootstrap-p value is taken into account in Table 6. Upon considering the Bootstrap value, the H_0 hypothesis, which implies the existence of cointegration, is accepted. Therefore, it is understood that a strong long-term cointegration relationship exists among the variables.

4.4. Long-term AMG estimation and Dumitrescu-Hurlin's causality test results

The panel-wide AMG estimation results are presented in Table 7. According to the results of the analysis, the impacts of TI, GLO, TO, and RE variables on EF are negative and statistically significant. In other words, these variables have impacts on the improvement of EQ. On the other hand, another result obtained from the study is that the FD variable has a detrimental impact on the EQ of the countries included in the analysis. The impact of FD on EF is positive and statistically significant at the 10 % significance level.

The finding that TI improves EQ is consistent with the studies of [27, 157]. In the study, the findings that GLO, TO, and RE increase EQ by decreasing EF are similar study results of [109,158]; and [159]; respectively. Another finding obtained in the study is FD causes ED. This finding is consistent with the study results of [160,161].

The country-specific AMG results have been reported in Table 8. According to the results, TI has a negative impact on EF in the economies of Japan, the United States, Korea Rep., France, Germany, Thailand, and Sweden. In other words, TI plays an important role in improving the EF in countries with a high level of FD. In Japan, FD has a negative impact on EF, whereas it has a positive impact in Spain and Germany. Another finding from the study is that GLO has a negative impact on EF in Switzerland, Japan, Spain, and France. On the other hand, this impact is positive in Korea Rep. and the Netherlands. Upon evaluating the role of RE on EF, it is seen that TO plays an important role in reducing environmental pollution in the economies of the United Kingdom, Korea Rep., Germany, Sweden, Norway, and Portugal. RE causes ED only in Switzerland. Lastly, by considering the impact of RE on EF, it is found that this impact is negative in Switzerland, the United States, the United Kingdom, Korea Rep., Spain, France, Germany, and Netherlands. Upon

Table 3
Cross-sectional dependence test results.

Variables	lnEF	lnTI	lnFD	lnGLO	lnTO	lnRE
Breush-Pagan LM	876.486* (0.000)	989.716* (0.000)	1804.874* (0.000)	2402.756* (0.000)	1558.745* (0.000)	1328.862* (0.000)
Pesaran scaled LM	58.224* (0.000)	66.617* (0.000)	127.040* (0.000)	171.358* (0.000)	108.796* (0.000)	91.756* (0.000)
Bias-corrected scaled LM	57.974* (0.000)	66.367* (0.000)	126.790* (0.000)	171.108* (0.000)	108.546* (0.000)	91.506* (0.000)
Pesaran CD	15.455* (0.000)	2.574* (0.010)	41.902* (0.000)	48.933* (0.000)	35.760* (0.000)	28.614* (0.000)

Note: The *p*-values are given in parentheses. * denotes significance at 1 % level.

Table 4
Slope homogeneity test results.

	Model 1
$\tilde{\Delta}$	6.790[a] (0.000)
$\tilde{\Delta}$ adj	8.141[a] (0.009)

Note: The *p*-values are given in parentheses.
[a] denotes significance at 1 % level.

Table 5
CADF and CIPS unit root test results.

Variables	CADF test statistic for constant		CIPS test statistic for constant	
	level	first difference	level	first difference
lnEF	−2.229**	−4.926*	−2.396**	−6.043*
lnTI	−1.958	−3.820*	−2.116	−5.871*
lnFD	−2.526*	−4.080*	−2.630*	−5.393*
LnGLO	−2.157***	−4.310*	−2.820*	−6.022*
lnTO	−2.067	−3.749*	−1.809	−5.661*
lnRE	−2.176***	−4.528*	−2.420**	−5.970*

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

Table 6
Westerlund-Edgerton's LM bootstrap cointegration test results.

Test	LM Statistics	Asymptotic-p Value	Boostrap-p Value
LMN^T	17.106	0.000	0.815

Note: The number of bootstrap iterations is 1000. The test result is obtained with the constant and trend models.

Table 7
Panel-wide AMG estimation results.

Dependent Variable: EF	Coefficient	P-Value
lnTI	−0.057*	0.006
lnFD	0.053***	0.081
lnGLO	−0.673**	0.028
lnTO	−0.195***	0.079
lnRE	−0.2385*	0.000
Constant	5.973*	0.000
Wald χ2	35.72	
Prob > χ2	0.000	
RMSE	0.055	
# of Observations	406	
# of Countries	14	

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

evaluating the country-specific analysis results, the most important determinants of EF in these countries are seen to be TI, TO, and RE. It is understood that these variables are important factors in reducing environmental pollution in approximately half of the countries.

After estimating the panel-wide and country-specific long-term coefficients of the variables using the AMG estimator, the causality links in the model are examined. Table 9 displays the findings of Dumitrescu-Hurlin's causality test. As seen in Table 9, TI, GLO, and RE have bidirectional causality relationships with EF. However, a unidirectional causality relationship is found running from FD to EF, and from to EF.

The causality relationship between TI and EF detected in the study are consistent with the studies of [24,136]. In the study, the causality relationships between FD, GLO, TO, RE, and EF determined show similarities with the studies of [24,92,107] and [132]; respectively.

5. Discussion

The finding that TI reduces ED is consistent with the finding of [27] claiming that TI reduces the EF for developing countries and regions of Asia, Africa, Latin America, and the Caribbean over the period 1990–2016. Also, this finding exhibits similarities with the findings of [157] asserting that TI improves EQ for the Chinese economy over the period 1980–2016. Similarly, it is also consistent with the findings of [162] for the N-11 countries over the period 1990–2017, and [50] for the Pakistani economy over the period 1980–2018. In this study, a bidirectional causality relationship between TI and EF is found to be consistent with the findings of [24,136].

Our findings regarding the negative impact of FD on the environment are consistent with the findings of [163] for Pakistan over the period 1985–2014 [160]; for Egypt over the period 1971–2014 [161]; for the South Asian economies for the 1990/2014 period. These researchers, since FD leads to ED, stated that financial resources should have been allocated among environmentally-friendly areas, technological innovations should have been shifted to the RE sector, the government should have encouraged loans that reduce resource consumption such as R&D and green finance, which are necessary for efficient production, and improvement of EQ. In this study, a unidirectional causality relationship from FD to EF is identified. [24,82,164]; and [68] also presented similar evidence.

The finding that GLO improves EQ is consistent with the findings of [1] who investigated the impacts of different GLO dimensions on carbon emissions in 137 developed and underdeveloped countries over the period 1970–2014, suggesting that social and cultural GLO significantly reduced carbon emissions of developed countries. It is also consistent with the findings of [165] conducted for the Sub-Saharan African region over the period 1980–2015, and [158] conducted for the E7 economies between 1990 and 2016. These findings assert the importance of economic integration among countries to reduce ED. Besides, the findings of the bilateral causal relationship between GLO and EF obtained in this study are compatible with the findings presented by Refs. [65,92] in their studies.

The finding suggesting that TO reduces the EF is consistent with the findings of [114] conducted for the EU [115]; for the EU; Lu (2020) for 13 Asian countries; and [109] for Pakistan. These findings can be attributed to the fact that advanced technologies lead to environmentally-friendly production processes in developed countries. The existence of a unidirectional causality between TO and EF is similar to the findings of [107,116].

The finding that RE consumption improves EQ is consistent with the findings of [101] conducted for 23 countries sample over the period 1985–2011, Dogan and Ozturk (2017) for the US economy over the period 1980–2014 [166], for China between 1980 and 2014 [91], for 18 developing countries over the period 1990–2015, and [159] for the

Table 8
Country-specific AMG estimation results.

Countries	lnTI	lnFD	lnGLO	lnTO	lnRE	Constant
Switzerland	0.005 (0.765)	0.031 (0.684)	−1.744* (0.000)	0.334* (0.001)	−0.659* (0.000)	9.820* (0.000)
Japan	−0.014*** (0.099)	−0.244** (0.032)	−0.542* (0.000)	−0.026 (0.670)	−0.006 (0.904)	4.043* (0.000)
United States	−0.168* (0.008)	0.094 (0.450)	0.827 (0.289)	−0.182 (0.156)	−0.216* (0.008)	1.574 (0.602)
United Kingdom	−0.028 (0.715)	0.031 (0.910)	−0.786 (0.562)	−0.433*** (0.097)	−0.085* (0.010)	4.235 (0.520)
Korea Rep.	−2.028* (0.000)	0.078 (0.917)	4.217* (0.002)	−1.117* (0.000)	0.493* (0.000)	5.272 (0.154)
Spain	−0.087 (0.231)	0.421* (0.002)	−1.718** (0.042)	−0.009 (0.942)	−0.415* (0.000)	10.662* (0.005)
France	−0.201* (0.001)	−0.197 (0.187)	−1.190*** (0.077)	0.229 (0.169)	−0.471* (0.000)	8.618* (0.004)
Germany	−0.129*** (0.094)	0.450* (0.000)	−0.977 (0.182)	−0.454** (0.027)	−0.093** (0.013)	9.074* (0.002)
Thailand	−0.063** (0.012)	0.389 (0.479)	−0.205 0.610	−0.362 (0.000)	0.367** (0.013)	7.262* (0.000)
Sweden	−0.097** (0.024)	0.057 (0.691)	1.085* (0.001)	−0.515** (0.036)	−0.237 (0.199)	0.061 (0.956)
Netherlands	−0.016 (0.881)	0.108 (0.728)	1.990*** (0.088)	0.083 (0.786)	−0.218* (0.003)	−7.023 (0.237)
Norway	−0.006 (0.808)	−0.013 (0.931)	−1.137 (0.121)	−0.357*** (0.085)	−0.256 (0.586)	9.504* (0.002)
Denmark	−0.016 (0.789)	0.067 (0.692)	−0.517 (0.756)	0.276 (0.643)	−0.091 (0.318)	3.287 (0.626)
Portugal	0.009 (0.528)	0.141 (0.394)	−0.777 (0.476)	−0.495* (0.003)	−0.250* (0.002)	8.435*** (0.067)

Note: The *p*-values are given in parentheses. *, ** and *** denote significance at 1 %, 5 % and 10 % level, respectively.

Table 9
Dumitrescu-Hurlin panel causality test results.

Null Hypothesis	W-Stat.	Zbar-Stat.	p-value	Causality
lnTI ⇔ lnEF	12.697	5.697	0.000*	lnTI↔lnEF
lnEF ⇔ lnTI	9.750	2.750	0.005*	
lnFD ⇔ lnEF	5.261	6.101	0.000*	lnFD→lnEF
lnEF ⇔ lnFD	0.756	−0.643	0.519	
lnGLO ⇔ lnEF	16.059	9.059	0.000*	lnGLO↔lnEF
lnEF ⇔ lnGLO	13.093	6.093	0.000*	
lnTO ⇔ lnEF	14.477	7.477	0.000*	lnTO→lnEF
lnEF ⇔ lnTO	1.057	0.152	0.879	
lnRE ⇔ lnEF	18.9902	11.9902	0.000*	lnRE↔lnEF
lnEF ⇔ lnRE	11.9200	4.9200	0.000*	

Note: *, **, and *** indicate the significance level at 1 %, 5 %, and 10 %, respectively.
The symbols →, ↔, and ⇔ indicate a unidirectional, bidirectional, and does not homogeneous causality, respectively.

South Korean economy over the period 1971–2017 suggesting that RE consumption had a crucial role in improving the EQ. Upon evaluating the study in terms of causality, it is consistent with the findings of [167] conducted for Turkey, Kongbuamai et al. (2021) for BRICS countries, and [132] for financial resource-abundant countries regarding a bilateral causality between RE and EF.

The results of the study, which are largely similar to the empirical literature, are summarized in Figs. 3 and 4 in terms of long-term effects and causality between the variables, respectively.

6. Conclusion and policy implications

In this study, the mediating roles of TI and TO on the EF were explored using second-generation panel data analysis techniques. Besides TI and TO, the explanatory variables of GLO, FD, and RE were also included in the EF model. Regarding the finding that TI improves EQ, it could be claimed that in countries with high FD, TI encouraged the transition to clean energy by mitigating fossil fuel dependence. Therefore, assuming priority to R&D investments that would encourage TI in these countries was of great importance in terms of combating ED. Moreover, increasing the number of environmentally-related patent applications should have been among the environmental protection policy measures of the government. The finding that GLO and TO reduced ED could have been associated with the use of modern innovative production methods that caused low carbon emissions and facilitated the flow of environmental-friendly technology to related countries. It could have been claimed that the environmental awareness of those countries, that completed their development processes, was high.

The reasons such as the limited amounts of fossil-based energy

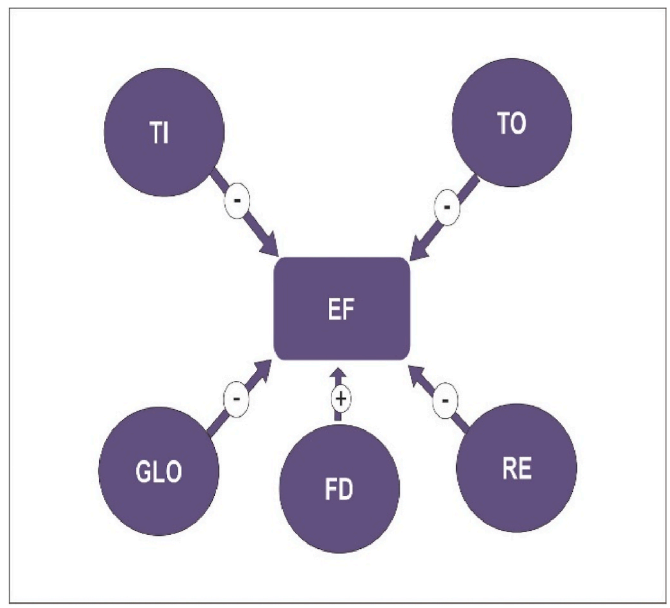

Fig. 3. Long-term effects of variables.

resources in the globe, related environmental problems, and foreign resource dependence of countries for production have increased the interest in RE resources. Therefore, the finding that RE plays a substantial impact in improving EQ can be considered as an essential policy recommendation in the countries included in this study to prioritize investments in RE resources and minimize ED. Research and development for eco-friendly projects and allocation of funds in renewable energy projects on behalf of public and private partnerships investments will pave the for RE projects and realizing sustainable development goals (SDGs) in these countries. The authorities should also facilitate individuals and companies utilizing renewable energy sources in the shape of subsidies and offering relevant incentives. Another result obtained from the study is that FD has a detrimental influence on environmental sustainability. To attain sustainable development goals, it is crucial to provide funds to well-developed financial institutions and R&D activities for encouraging green finance and facilitating the development of financial institutions. Therefore, it would be beneficial for policymakers in these countries to direct financial resources toward clean energy production and consumption, and for governments to encourage and support projects and practices in this field. This goal can be achieved via the introduction of novel financial tools such as green banks, the issuance of green banks, carbon market instruments, and green central banking.

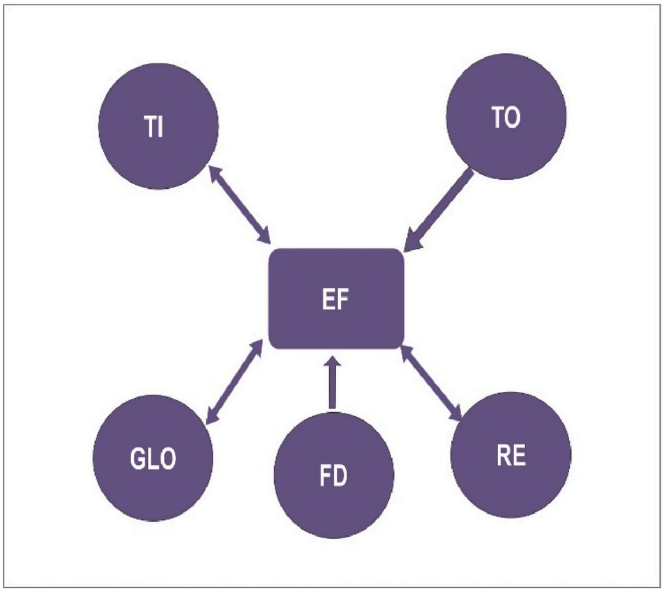

Fig. 4. Causality relationship between variables.

The obtained results provide a basis for formulating the following policy recommendation. Policymakers should collaborate with industry stakeholders to establish clear targets and guidelines for sustainable transformation, ensuring alignment with environmental sustainability goals. Additionally, strengthening financial support for green investments is crucial in accelerating the transition to a low-carbon economy. By facilitating access to financial resources and creating an enabling investment environment, governments can drive the adoption of environmentally friendly practices and technologies.

The study has some limitations and suggestions for future studies. This study concentrates on the determinants of EF in countries with a high level of FD. In future studies, country-specific classification of the determinants of EQ can be made by considering income levels. Thus, comparisons of countries with different income levels can be included. Furthermore, the EF model can be estimated for the country groups that account for the majority of EF. Thus, policy recommendations can be developed for these country groups. Future studies designing their analyses following these constraints would enable the development of more detailed policy recommendations for improving EQ. We hope to bridge these gaps in our future research works.

Author(s) contributions

Mesut Doğan: Conceptualization, Methodology, Supervision, Writing – original draft. Assad Ullah: Supervision, Writing – review & editing, Visualization. Betül Altay Topcu: Writing – review & editing. Haifa Saadaoui: Writing – review.

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Declaration of competing interest

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

Data Availability

Data will be made available upon reasonable request.

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