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# Does economic complexity matter for environmental sustainability? Using ecological footprint as an indicator

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**Abstract**
The current decade has witnessed the rise of empirical research in the domain of ecological footprint which has become a major scholarly area among environmental researchers. However, many key factors determining ecological footprint have been inadequately dealt within the existing body of knowledge. The current research aims to explore the association between economic complexity, human capital, renewable energy generation, urbanization, economic growth, export quality, trade and ecological footprint for the top ten economic complex countries. This study applied panel data estimators, for instance, fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS) and the system-GMM long-run estimators from 1980 to 2017. The long-run estimates reveal that economic complexity, economic growth, export quality, trade and urbanization increase ecological footprint. Human capital and renewable energy generation help to mitigate ecological footprint. We conclude that investment in more renewable energy generation and its consumption and efficient use of human capital will improve economic complexity, export quality, and environment in developed and developing countries.

**Keywords** Economic complexity · Human capital · Export quality · Ecological footprint · Environmental sustainability

**JEL classification** O33 · C32 · Q53 · Q56

## 1 Introduction

Climate change and environmental degradation are the biggest challenges faced by humanity today. In 2020, swarms of desert locust threatened food security in Africa, the Middle East, and South Asia amidst the global issue of the COVID-19 pandemic. It is feared that the total number of people living below the poverty line can plummet to 132 million by 2030 if the climate change issue is not tackled promptly. These recent most global challenges are ascribed as failure to act timely to the rapid environmental changes in the last

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few decades. (Gorji & Gorji, 2021; Work Bank, 2021). On the other hand, extremely high temperatures, harsh weathers and abrupt sea-level rise disturb the production of goods and services due to a shift in factors of production (Dellink et al., 2017). A global effort to protect the environment and ecosystem that sustain lives and economies is the only way to get back on track to improve the well-being of the people through environmental protection.

Globally, a vast research literature exists on analyzing the environmental condition using different proxies of environmental pollution over time. Among these, greenhouse gases (GHGs) emission is of central importance. Due to readily available data and holding largest share in GHG emission, a plethora of environmental economics research literature takes $CO_2$ emissions as a proxy of environmental degradation (Ahmed et al., 2019; Can & Gozgor, 2017; Danish, 2019; Sharif Hossain 2011; You & Lv, 2018). But, from a sustainable development perspective, a more aggregated proxy, the ecological footprint (EF) is being widely used to measure environmental hazards and sustainability (Bello et al., 2018; Ulucak and Bilgili, 2018; Bilgili & Ulucak, 2020; Chu, 2020). Researchers have been using EF to measure environmental performance and sustainability over time (Al-Mulali et al., 2015; Ru, 2010; Shahzad et al., 2021a, b; Wiedmann & Barrett, 2010). The ecological footprint is the most important metric that represents human-centered pressure on environmental condition through resources consumption by individuals in the form of finished goods and relates it to the planet earth overall regeneration capacity (Rees, 1992).

This study is an effort to explore the interlinkages between ecological footprint and economic complexity, human capital, trade, export quality and energy use in the top ten economic complex countries. Economic complexity is among the main explanatory variables for this study because it encompasses all aspects of production like competency, knowledge, and advancement (Hausmann et al., 2019). The top ten economic complex countries' have shown remarkable economic growth with industrialization and urbanization in the recent past. Due to this transformation from agriculture based to complex industrial economies, energy consumption in these economies has also increased manifolds. For this reason, these economies are considered to have a leading contribution to GHG emissions, and their ecological footprint will determine the fate of the global environment in the future. In this backdrop, this study is a crucial addition to the already ecological footprint literature (Bashir et al., 2020; Shahzad et al., 2020).

The ecological footprint helps to determine and manage resource usage in different sectors of the economy and plays a central role in economic development (Hailu & Kipgen, 2017). According to Hidalgo and Hausmann (2009), economic complexity refers to any economy's productive capacity possessing a specific economic and energy consumption structure having a specific impact on the environment. Economic complexity is the amount of knowledge that is used by society to built productive structure of the economy. Economic development is driven by knowledge and holds the position of accurate predictor of growth. It has strong relationship with environmental conditions. A more complex economy provides forum for the production of knowledge-intensive production structure and protect environment through knowledge and technology adoption (Hausmann et al., 2014). Through industrialization and product diversification, economic complex countries move to knowledge-intensive technologies such as energy-efficient goods and renewable energy generation to keep the economy green (Swart & Brinkmann, 2020). Renewable energy generation and consumption is the best solution to environmental protection without hampering economic growth. International Energy Agency (IEA) (Energy 2019) claims that renewable energy generation is highly on the rise globally, while Bölük and Mert (2014) claim that RE consumption contributes around ½ less per unit of non-RE energy consumed. Raza et al. (2021) claim that investing in clean energy production technology can substantially decrease carbon emission. How RE generation affects EF has attracted the attention of researchers globally (Danish, 2020; Destek & Sinha, 2020; Nathaniel & Khan, 2020; Pata, 2021). Advanced countries have higher investments in renewable energy generation and efficient production. Neighboring countries can also adopt those renewable energy generation policies and methods later through policy learning and imitation. This is called the renewable energy potential similarity effect. Another impact of generating renewable energy in those developed economies will be the positive externality called as knowledge spillover effect (Shahnazi & Dehghan Shabani, 2020).

Effective resource utilization, productive capacity and environment (EF) are greatly affected by human capital (Gylfason, 2001; Lederman & Maloney, 2006; Zafar et al., 2019). A high level of knowledge is necessary for a technological breakthrough to protect the environment. According to Kwon Dae-Bong (2009), there are three categories of human capital: (i) human capital stock-general education and related experience (ii) task-oriented human capital-including all task related skills & knowledge (iii) firm specific human capital-firm related education & skills. Human capital affects ecological footprint as they get more knowledge on energy efficiency, energy security and environmental issues (Bano et al., 2018). Human capital determines the effective use of natural resources such as croplands, grazing lands and fishing which are the raw materials for environment friendly energy generation and mitigate the $CO_2$ emissions produced by humans as well (Zafar et al., 2019; Zallé, 2019). Thus human capital investment can also act as a catalyst in achieving climate related sustainable development goals (Kwon Dae-Bong, 2009; Lan et al., 2012).

Export quality is one of the drivers of economic growth (Bashir et al., 2020). The allocation of resources should be in the most efficient way, while the quality of the products should be at par with the global standards to achieve export competitiveness to guarantee steady economic growth (Wang et al., 2021). Export quality mitigates carbon emissions and thus improves environmental condition (Gozgor & Can, 2017). A strong relationship exists between exports quality and ecological footprint (B. Dogan et al., 2020). Exports induced economic growth will be helpful to achieve the SDG-8 (Decent Work and Economic Growth) only if the climate-related spillovers of industry are managed efficiently (Wackernagel & Rees, 1998).

Trade openness is the characteristics of the developed world to boost economic growth. On the other hand, trade has significant impact on environmental quality (Grossman & Krueger, 1991). Trade openness favors shifting of polluting industries from developed to developing countries positively impacting environmental quality in developed countries due to strict environmental compliance in treating developing countries as Pollution Haven Hypothesis—PHH (Copeland, 2005; Copeland & Taylor, 1994). The industries in developed countries would have a paradigm shift to less polluting industrial set-up in the light of Stolper-Samuelson theorem and consider the environment as normal good and protect environment after a point of economic growth (Ling et al., 2015). Thus, there exists strong interdependence between EF and trade (Global Footprint Network 2020). Although limited literature has explored the trade-EF nexus (Ahmed et al., 2020a, b; Destek & Sinha, 2020; Nathaniel & Khan, 2020), specific studies on selected countries are missing.

To measure the impact of key variables, we include urban population and economic growth in the estimation model, as they are important determinants of environmental degradation. A wide literature has used these variables to explore their impact on ecological footprint as outlined in a literature review. The case of the leading EC economies should be studied thoroughly because these economies comprise of the more diverse product (highly economic complex); specialized know-how (have better human capital) and are also capable of producing sophisticated products (better quality of exported goods and trade openness). Manufacturing of such products requires a high energy intensive industrial base which might impact ecological footprint greatly. However, the literature has largely ignored the roles of selected variables in these economies. To the best of our knowledge, the interrelationships among these variables have not been studied together (Neagu, 2020; Ulucak & Bilgili, 2018). It will be a seminal study to fill this research gap. Leading complex economies will have more diverse and sophisticated products in its export basket and can play a dominant role for sustainable development and environmental sustainability. Hence from this perspective, our study will give new insights about these economies and propose some useful policy guidelines for transitional and developing economies to adopt these measures for sustained economic growth and environmental sustainability.

The rest of the paper has been structured as follows: Sect. 2 contains the literature review. Section 3 is titled as materials and methods, and further contains model specification, data and econometric strategy. Section 4 discusses results, whereas Sect. 5 is about policy and managerial implications. Lastly, Sect. 6 presents the 'conclusion' along with some limitations and further avenues of research in this field.

## 2 Literature review

Economic growth has a direct impact on the environment. Many studies have tried to explain this relationship using different environmental and economic proxies (Bekun et al., 2019; Destek & Sinha, 2020; Dong et al., 2020; Neagu & Teodoru, 2019; Youssef et al., 2020). Among all the environmental and economic indicators, EF and ECI have attracted much attention in the past few years (Buhari et al., 2020; Chu, 2020; Pata, 2021). The following seminal research work used EF to explain the relationship between environment and economic activities.

Shahzad et al. (2021a, b) studied the relationship between ECI and EF in the US. They found that energy consumption and ECI have a positive relation with EF, which deteriorate the environment. Pata (2021) also conducted a study analyzing ECI and EF in the US. The results show that there is an inverted U-shaped relationship between ECI and EF in the USA. However, RE and globalization have a negative relationship with EF, Neagu (2020) explained the relationship between ECI, GDP, Non-RE and EF in top ECI countries. The study claimed the positive relationship of income growth, energy consumption and ECI with EF. Yilanci and Pata (2020) applied to study the impact of ECI, energy consumption and economic growth on EF in China and found that ECI and energy consumption deteriorate the environment. Also, the EKC hypothesis does not exist in China for economic growth and EF.

Bilgili et al. (2020) analyzed the impact of globalization on EF Turkey. They concluded that social and economic globalization has a positive relationship with EF. In addition, human capital, capital stock, political globalization, and financial globalization improve EF. Danish, Ulucak, and Khan (2020) linked human capital, urbanization, and resources with EF in BRICS countries. They applied FMOLS and DOLS on data from 1992 to 2016 and concluded that urbanization, natural resource rent, and RE improve environmental conditions by negatively affecting EF.

Similarly, Ahmed et al. (2020a) explored the relationship between trade, human capital, urbanization, energy consumption, economic growth and ecological footprint. According to the results, human capital improves, while urbanization, GDP and energy consumption deteriorate the environment. Ahmed et al. (2020a, b) reported that urbanization, natural resources, and economic growth have an increasing relationship with EF. However, human capital and interaction of human capital and urbanization reduce EF in China. Nathaniel et al. (2020) claimed urbanization and non-RE increases EF. However, economic growth showed mixed relation with EF in different CIVETS countries while RE and trade openness mitigate environmental degradation. Destek and Sinha (2020) conducted a study on OECD countries, showing that economic growth has an inverted U-shaped relationship with EF. Also, RE and trade openness decrease, while non-RE increase EF. Nathaniel and Khan (2020) studied the relationship between energy consumption, trade, urbanization and ecological footprint. They found that the coefficients of Non-RE, GDP, and Trade are positive while RE negative but insignificant, former variables show adverse impact on EF.

Furthermore, the study of Alola et al. (2019) showed that RE, Non-RE, GDP are deteriorating environment. Fertility rate and trade openness have a negative relation with EF. Zafar et al. (2019) found that the relationship of EF with human capital, FDI, and natural resources is decreasing. Also, EF has a positive or increasing relationship with energy consumption and economic growth. Destek et al. (2018) stated that EKC holds in EU concerning EF, and trade openness improves the environmental condition. A similar study with EF, Ulucak and Bilgili (2018) proved the EKC hypothesis in all countries from lower to higher income group. In addition, human capital and bio-capacity improve EF, while trade openness harms the environment. Uddin et al. (2017) applied DOLS and FMOLS to analyze the relationship between EF and economic indicators. In the DOLS model, financial development and trade openness have adverse effects, while GDP positively relates to EF. In FMOLS, all variable exhibited positive relation with EF. Charfeddine and Mrabet (2017) showed that social factors improve the environment while political index and energy consumption deteriorate the environment by having positive relationships with EF. Rudolph and Figge (2017) studied the relationship between GDP, energy intensity, KOF index, and EF in 146 countries. All the variables and their components showed a positive relation with EF except social globalization.

The focus of our study is the set of top 10 ECI countries. Unlike Neagu (2020), which analyzes the EF-ECI nexus for 48 leading ECI economies, sample countries of this study are less heterogenous in terms of economic growth, economic structure and export quality. By expanding the sample set of countries, the heterogeneity among countries become more evident. Therefore, this study evaluates the impact of ECI, human capital, export quality, trade, urbanization, and GDP on EF using FMOLS, DOLS, and system-GMM. This study will contribute to the existing literature by examining the impact of these social and economic indicators on the comprehensive environmental indicator in the most complex group of countries.

## 3 Materials and methods

Before moving to the construction of an econometric model, data description and estimation techniques, we highlight the research framework for the study. EF since its inception in 1990s has been used in various research aspect. Considering EF as the best proxy for environmental sustainability, we explore the dynamic impacts of certain key variables in selected countries. Economic complexity affects EF through productive structure and product diversification, knowledge-intensive technological adoption and production, renewable generation, and energy-efficient goods production (Hausmann et al., 2014; Swart & Brinkmann, 2020).

Human capital affects EF through efficient resource utilization (Zafar et al., 2019; Zallé, 2019) technological breakthrough by knowledge on energy efficiency and security (Bano et al., 2018). Furthermore, trade openness affects EF through improved efficient resource allocation (Wang et al., 2021), efficient management of spillover effects (Wackernagel & Rees, 1998) and product competitiveness for improving export quality products using energy efficient industrial set-up (Swart & Brinkmann, 2020).

The possible interaction of urbanization with EF is one example of the scenario in which the environment is being affected by the rising population. Ahmed et al. (2020a, b) and Sun et al. (2018) also hint at the factors through which urbanization affects the environment. The current study develops a research framework explained in Fig. 1 following some other studies (Doğan et al., 2019; Nathaniel et al., 2020; Wang et al., 2021; Zallé, 2019).

## 3.1 Model specification

After a detailed analysis of recent most research literature (Bashir et al., 2020; B. Dogan et al., 2020; Doğan et al., 2020; Shahzad et al., 2020; Shahzad, et al., 2021a, b), we have devised the following general econometric model for estimation,

$$EF = f(ECI, RE, HC, GDP, UP, EQ, TRD) \quad (1)$$

where EF denotes ecological footprint, ECI illustrates economic complexity index, RE indicates renewable energy generation, HC shows human capital, GDP demonstrates gross domestic product, UP shows urban population, EQ displays export product quality and TRD shows trade openness. For the purpose of decreasing dispersion present in the data, some of the variables are also converted into their natural logarithms. Such a conversion also helps in diminishing the issues which are associated with multicollinearity and

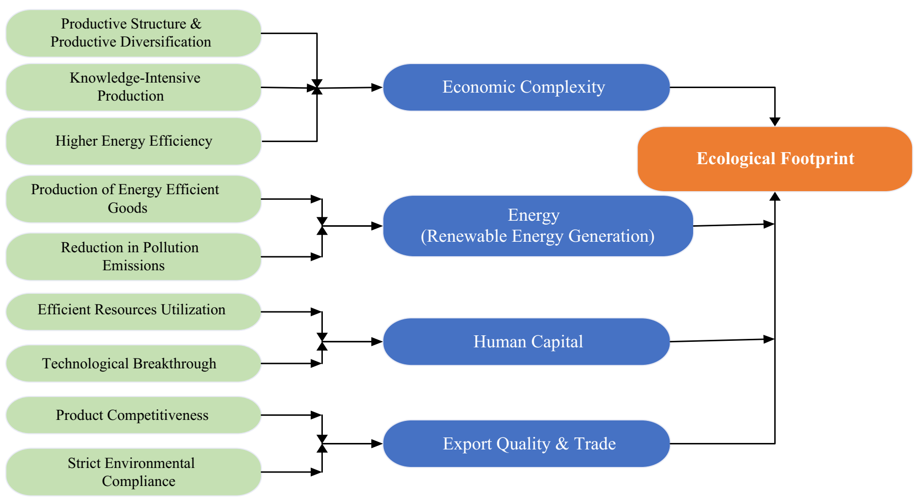


**Fig. 1** Analytical Framework

heteroscedasticity. Destek and Sinha (2020) have proved that, as compared to the simple linear data, log-linear transformation produces efficient and reliable results.

Economic complexity is a measure of society's knowledge used in the production of diversified exported goods. ECI shows the ranking of countries based on how diversified and complex export basket a country has? ECI is calculated based on exports data reducing the country's economic system into two dimensions; the 'diversity' and 'ubiquity' of products in the export basket (Hausmann & Hidalgo, 2011). We have devised two models: model 1 uses ECI, while model 2 use export quality and trade. The logic behind using EQ and TRD in the 2nd model is to check the individual effects of these two variables instead of single variables (ECI). The two dimensions of trade openness; trade volume as % age of GDP and its quality, highlighting in-depth association among the variables of interest. In fact, it is the diversified nature of export products and trade goods which contribute much toward the economic complexity index.

Hence the multivariate models in log-linear form can be written as:

Model-1

$$\ln \mathrm{EF}_{\mathrm{it}} = \infty + \beta_{1\mathrm{t}}\mathrm{ECI}_{\mathrm{it}} + \beta_{2\mathrm{t}}\mathrm{RE}_{\mathrm{it}} + \beta_{3\mathrm{t}}\mathrm{HC}_{\mathrm{it}} + \beta_{4\mathrm{t}} \ln \mathrm{GDP}_{\mathrm{it}} + \beta_{5\mathrm{t}} \ln \mathrm{UP}_{\mathrm{it}} + \mu_{\mathrm{it}} \quad (2)$$

Model-2

$$\ln \mathrm{EF}_{\mathrm{it}} = \infty + \beta_{1\mathrm{t}}\mathrm{RE}_{\mathrm{it}} + \beta_{2\mathrm{t}}\mathrm{HC}_{\mathrm{it}} + \beta_{3\mathrm{t}} \ln \mathrm{GDP}_{\mathrm{it}} + \beta_{4\mathrm{t}} \ln \mathrm{UP}_{\mathrm{it}} + \beta_{4\mathrm{t}} \ln \mathrm{EQ}_{\mathrm{it}} + \beta_{4\mathrm{t}} \ln \mathrm{TRD}_{\mathrm{it}} + \mu_{\mathrm{it}} \quad (3)$$

where $t$ represents years (1980, 1981,…, n), and μ signifies the error term.∞ is a constant term. $\beta_1, \beta_2, \beta_3 \ldots \ldots .\beta_5$ are the coefficients of economic complexity, human capital, renewable energy, GDP, and urban population. Similarly, the index i is a number of countries (1, 2, 3,…, n). The results of both the models have been compared in the results discussion section.

### 3.2 Data

Panel data technique has been employed in the current study for estimation purposes. The sample of countries includes Austria, Ireland, Finland, UK, Japan, Singapore, South Korea, Sweden, Switzerland, and USA and the time period for the study is from the year 1980 to 2017. Data for EF have been collected from the global footprint network. Economic complexity data are obtained from https://oec.world/en/resources/data/ (Hausmann & Hidalgo, 2011). Human capital data have been taken from The Penn world tables (PWT) 9.0 database (Feenstra et al., 2015; Zafar et al., 2019). Data for renewable energy generation and export product quality have been gathered from EIA and IMF database, respectively (International Monetary Fund, 2020). For the remaining variables urban population, trade and economic growth, data have been collected from the world development indicators database (World Bank, 2020). Further specifications of the variables have been described in the following Table 1:

### 3.3 Econometric strategy

A common assumption regarding panel data methodology is that variations in cross-sectional units can be captured through fixed constants to address heterogeneity. Still, the possibility of individual variations exists due to the difference in the structure of the economy. If such variations are not addressed, the results are likely to be biased, and

**Table 1** Variables description and sources of data

| Symbol | Description and measurement | Source |
|---|---|---|
| *Dependent Variable* | | |
| lnEF | Ecological footprint (total GHA) | Global Footprint network |
| *Independent Variables* | | |
| ECI | Economic Complexity Index | https://oec.world/en/resources/data/ |
| lnRE | Renewable electricity generation (billion Kwh) | Energy Information Administration (EIA) |
| *Control Variables* | | |
| HC | Human capital index | Penn world Table |
| lnGDP | GDP per capita (constant 2010 US$) | World Bank |
| lnUP | Total urban population size (number) | World Bank |
| lnEQ | Export product quality | International Monetary Fund |
| TRD | Trade (% of GDP) | World Bank |

inferences drawn after that are improper. It is for this reason that this study accounts for the following checks: (a) Cross-sectional dependence (b) stability of data series through panel unit root tests, (c) long-term association between variables is checked through panel cointegration method (d) FMOLS, DOLS and system GMM (SGMM) methods are used in case cointegration among variables is confirmed in order to assess long-term elasticity between the explained and the explanatory variables. Endogeneity problem in the regressors has been addressed by the use of GMM estimator. The GMM estimator uses a set of instrumental variables which is comprised of all available lags in the difference of the endogenous variables and the strictly exogenous regressors (Al-Mulali et al., 2015; Arellano & Bond, 1991; Fotis & Polemis, 2018).

The present study employs the system-GMM (SGMM) estimator which is comprised of previous instruments as well as the lagged values of the dependent variable (Blundell & Bond, 1998). In case of dynamic panel data, the system GMM is an appropriate estimator since it solves the endogeneity problem arising out due to the possible association among independent variable and the error term (Çoban & Topcu, 2013). On the other hand, FMOLS and DOLS are efficient techniques to solve endogeneity issues (among regressors) and serial correlations (among error terms). The main difference between FMOLS and DOLS is that the former uses a nonparametric approach to tackle endogeneity and autocorrelation, while the latter employs a parametric approach by including lags and lead values of the explanatory variables (Sun et al., 2018). In the small sized sample, DOLS' results are very improved and very efficient, as indicated by Danish et al. (2020) and Neagu and Teodoru (2019). Cross dependence can also be tackled through the DOLS technique since it acquires country-specific coefficients and then generates those results which are balanced, efficient and consistent. E. Dogan and Seker (2016) postulated that weighted criteria of DOLS and FMOLS methodologies could address heterogeneity issues in the cointegrated and long-run panel. Furthermore, there are many studies which have already employed the FMOLS and DOLS methodologies in order to estimate long-run parameters (Dogan & Aslan, 2017; Sadorsky, 2009).

**Table 2** Descriptive Statistics

| Variable | Mean | Std.Dev | Min | Max | VIF | Correlation |
|---|---|---|---|---|---|---|
| lnEF | 18.10 | 1.79 | 14.41 | 21.84 | | 1.000 |
| ECI | 1.76 | 0.43 | 0.16 | 2.62 | 2.85 | 0.48*** |
| lnRE | 3.32 | 1.96 | – 1.60 | 6.58 | 2.26 | 0.71*** |
| HC | 3.17 | 0.39 | 1.65 | 3.97 | 3.52 | 0.52*** |
| lnGDP | 10.46 | 0.51 | 8.21 | 11.26 | 2.92 | 0.41*** |
| lnUP | 16.44 | 1.51 | 14.45 | 19.40 | 2.52 | 0.73*** |
| lnEQ | 0.27 | 0.08 | – 0.06 | 0.60 | 1.23 | – 0.10*** |
| TRD | 98.51 | 93.32 | 16.01 | 437.32 | 3.73 | – 0.44*** |

***$p<0.01$, **$p<0.05$, *$p<0.1$

**Table 3** Cross-sectional dependence test results

| Test | Statistic | Prob |
|---|---|---|
| Breusch-Pagan LM | 75.02*** | 0.003 |
| Pesaran scaled LM | 7.01*** | 0.000 |
| Pesaran CD | 2.03* | 0.042 |

***$p<0.01$, **$p<0.05$, *$p<0.1$

## 4 Results and discussion

The empirical estimation starts with the study of descriptive statistics, which have been reported in Table 2. Economic complexity variable 'ECI' has 1.76 average value. The average value of EF is 18.10 gha per capita, which is very high compared to the global average, which is 2.8 gha per capita, whereas the maximum value of EF reaches 21.84 gha per capita. On the same account, the average value of urbanization is 16.44, which is significantly lower than the global average of 54%, whereas the maximum values reach to 19.40. The mean value of GDP per capita is 10.46 constant 2010 USD which depicts high growth in the top 10 ECI economies. Table 2 further shows the Pearson correlation statistic which is positive for all variables except export quality and trade. It implies that there is positive association of ecological footprint variable (EF) with all independent variables except export quality and trade. Multicollinearity among independent variables has also been examined by the variance inflation factor (VIF) method in the sixth column of Table 2. All the values of VIF are below 10, which depicts that there is no multicollinearity issue in our model.

Cross-sectional dependence (CD) examination is very important in panel data analysis through suitable methods and techniques (Pesaran, 2004). This study starts the analysis from CD therefore. Then, following the studies Pesaran (2004) and Hashem (2008) which propose variety of tests for CD, Table 3 shows these results and further reveals that the value of probability for the conducted tests is 0.000. Hence it shows the rejection of the null hypothesis at 1% significance level and proves the existence of cross-sectional dependence (CD).

After the confirmation of CD tests, the next step of the estimation is to check the stationarity in the data. This is done to check if the series carries a stationary process to avoid spurious regression estimation (Rafique, 2020). Panel unit root tests are feasible for this purpose since they also account for the cross-sectional dependence (CD).

**Table 4** Panel unit root test results

| Variable | CIPS | | CADF | |
|---|---|---|---|---|
| | Level | Δ | Level | Δ |
| lnEF | − 1.72 | − 5.61*** | − 1.09 | − 9.10*** |
| ECI | − 1.44 | − 5.56*** | − 1.31 | − 8.38*** |
| lnRE | − 1.44 | − 5.56** | − 0.32 | − 8.85*** |
| HC | − 1.86 | − 0.66*** | − 1.39 | − 1.97** |
| lnGDP | − 0.95 | − 4.01* | − 1.25 | − 5.52*** |
| lnUP | − 2.39 | − 1.01*** | − 2.38 | − 1.24* |
| lnEQ | − 0.71 | − 4.68*** | − 0.49 | − 2.94*** |
| TRD | − 1.59 | − 4.50*** | − 2.58 | − 9.28*** |

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$

**Table 5** Results of Westerlund cointegration test

| Statistic | Model-1 | | | | Model-2 | | | |
|---|---|---|---|---|---|---|---|---|
| | Gt | Ga | Pt | Pa | Gt | Ga | Pt | Pa |
| Value | − 3.78*** | − 6.69 | − 9.10*** | − 3.57** | − 4.46*** | − 6.64 | − 11.20*** | − 4.15** |
| Z-value | − 4.91 | 2.07 | − 2.57 | 1.77 | − 6.31 | 2.73 | − 3.76 | 2.11 |
| *P*-value | 0.000 | 0.976 | 0.005 | 0.038 | 0.000 | 0.997 | 0.000 | 0.031 |

***and ** are the level of rejection of no cointegration at 1% and 5% level of significance

Following Pesaran (2007), this study employs CIPS and CADF panel unit root tests, which can account for CD as well. Results of CIPS and CADF panel unit root tests are reported in Table 4. Hence the results show that null hypothesis of non-stationarity at 1% and 5% significance level can be rejected at the first difference. It further shows that variables are integrated in the first order, i.e., I (1) in both panels.

Presence of I (1) i.e., the stationary level at the first difference demands the examination of cointegration association among the variables in the study in order to check if the linear combination is stationary at the level too or not. Westerlund (2007) suggested a panel cointegration test for this purpose which can account for CD issue and investigate if linear combination of the series is stationary or the cointegration association exists. Panel cointegration test is further dependent on the panel (Pt, Pa) and group statistic (Gt, Ga).

Table 5 reveals the Westerlund cointegration test's results. As per the results, the Null hypothesis of no cointegration is rejected. It further implies that cointegration exists among the study variables, i.e., ECI, EF, renewable energy, human capital, urbanization, economic growth, trade, and export product quality. Since cointegration among variables has been proved, there exists long-run association too.

FMOLS, DOLS and SGMM estimators are shown in Table 6. The findings reveal that for both the models and techniques, the sign of impact of both the coefficients is same. In the first model, FMOLS estimation reveals the following results: 1% growth in ECI causes lnEF to increase by 0.83% while an increase of 1% in human capital causes lnEF to reduce by 3.48%. Thus, economic growth and urbanization impact lnEF positively

**Table 6** Estimation of long-run coefficients

| Model-1 | | | |
|---|---|---|---|
| Variables | SGMM | FMOLS | DOLS |
| ECI | 0.40*** | 0.83** | 0.49* |
| | (0.02) | (0.34) | (0.35) |
| lnRG | − 0.32*** | − 0.40*** | − 0.37*** |
| | (0.00) | (0.07) | (0.09) |
| HC | − 3.15*** | − 3.48*** | − 3.34*** |
| | (0.03) | (0.45) | (0.51) |
| lnGDP | 2.67*** | 3.02*** | 2.76*** |
| | (0.02) | (0.29) | (0.32) |
| lnUP | 1.07*** | 1.06*** | 1.06*** |
| | (0.01) | (0.09) | (0.10) |
| Model-2 | | | |
| Variables | System-GMM | FMOLS | DOLS |
| lnRG | − 0.20*** | − 0.21*** | − 0.19* |
| | (0.01) | (0.07) | (0.11) |
| HC | − 3.31*** | − 3.67*** | -3.56*** |
| | (0.03) | (0.35) | (0.55) |
| lnGDP | 2.92*** | 3.15*** | 3.09*** |
| | (0.02) | (0.26) | (0.41) |
| lnUP | 1.11*** | 1.15*** | 1.14*** |
| | (0.01) | (0.07) | (0.11) |
| lnEQ | 2.60*** | 3.02*** | 2.98** |
| | (0.07) | (0.90) | (1.44) |
| TRD | 0.07*** | 0.05*** | 0.02*** |
| | (0.01) | (0.04) | (0.07) |

Standard errors in parentheses

***$p<0.01$, **$p<0.05$, *$p<0.1$

and significantly. On the other hand, the impact of renewable energy generation on lnEF is 0.40% significantly negative.

In the second model, results of the FMOLS model reveal that if there is a 1% increase in human capital, lnEF will be decreased by 3.67%. Moreover, if there is an increase of 1% in lnRE then lnEF will be decreased by 0.21%. On the other hand, economic growth, export quality and trade influence lnEF positively and significantly.

The results of this study which show the positive relationship between ecological footprint (EF) and economic complexity (ECI) are fully endorsed by Yilanci and Pata (2020) and Shahzad et al. (2021a, b). Higher ECI ranking is based on the economy's productive structure, which involves efficient technology and resource allocation with more renewable energy usage. Due to the renewable energy spillover effect, developing countries may also adopt a similar pattern when developed countries generate more renewable energy. This will mitigate the ecological footprint (Neagu & Teodoru, 2019; Swart & Brinkmann, 2020). On the other hand, human capital has a negative relationship with an ecological footprint, as per the results of this study. It implies that human capital acts as a catalyst to improve environmental quality. In other words, human capital affects all those factors positively, which improve environmental quality. Those factors include knowledge, awareness and sustainable utilization of natural resources. In this study, both the models depict decreasing the impact of human capital on ecological footprint, which can be linked with skilled and responsible economic agents who can adopt more environmental-friendly behaviors. By adopting an environmental-friendly way of life, those economic agents can make their households, communities and countries more environmentally sustainable.

Our findings are in total accordance with the literature findings, which provides evidence about the significant impact of sustainability education on climate-friendly activities, for example, reducing, reuse, and recycling (Bano et al., 2018; Ulucak & Bilgili, 2018).

Export product quality and trade variables exhibit a positive association with the ecological footprint. It implies that with the increase in trade and production process (for making export goods), the environment quality gets compromised. GDP per capita and urbanization influence ecological footprint (EF) positively and significantly in both models. This result further shows that an increase in income levels further increases needs at individual levels, utilizing all kinds of resources and thus contributes to environmental degradation. The literature further strengthens this result of the positive relationship between GDP per capita and EF (Rudolph & Figge, 2017; Uddin et al., 2017; Ulucak & Bilgili, 2018).

Results of this study provide evidence that economic growth, trade and urbanization are found as main contributors in the increasing ecological footprint. This finding is totally justified by the supporting reality in the leading ECI countries which constitute the sample of this study (Austria, United Kingdom, United States, Finland, etc.). These economies have higher economic growth rates, urbanization and industrial activities, and transport-related projects. All of these activities consume more quantity of non-renewable energy sources and fossil fuels. The total volume of renewable energy always remains less than that of non-renewable energy levels. Hence in order to improve the quality of environment, renewable energy use should be increased and an energy substitutability plan is required for sustainable production at industrial levels of an economy (Wang et al., 2021).

## 5 Policy and managerial implications

In the light of our results, economic complexity should be at the forefront of economic growth policies and energy regulations since it has strong association with environmental sustainability. In this perspective, this study gives a policy recommendation about the adoption of clean energy policies and more usage of renewable energy (Destek & Sinha, 2020). It will be helpful to achieve SDG-7 (Affordable and clean energy) through maximization the productive capacity and pollution emissions reduction through renewable energy use. Moreover, High-end technologies such as (ICTs, Artificial Intelligence, blockchain) can also be leveraged for this purpose. (Rudolph & Figge, 2017; Uddin et al., 2017; Ulucak & Bilgili, 2018). The policy adopted in these economies will become a role model for developed and developing countries to regulate the energy sectors in order to ensure the sustainable production, distribution, and consumption of resources. Thus, it will be helpful to fulfil the SDGs 2030 agenda "Take urgent action to combat climate change and its impacts" globally.

The countries taken for this study are all developed ones where environmental regulations are already strictly implemented. Hence the current study recommends that these countries may encourage and provide incentives to polluting industries in developing countries to adopt clean energy for overall environmental sustainability. On the other hand, Human capital plays an important role in mitigating the ecological footprint in these countries since they are leading in the human development index. It implies that the masses in these economies have much awareness about environmental issues in general. This study recommends ensuring knowledge spillover from these developed economies to developing countries. High rates of urbanization are posing threats to increasing ecological footprints in developed and developing economies. A comprehensive rural development plan focused on renewable energy usage may be adopted to avoid negative externalities related to urbanization, impacting ecological footprint.

## 6 Conclusion

The present study was a humble contribution to the literature in an effort to explore the determinants of ecological footprint for the top 10 ECI economies. The time period of this study is 1980–2017, and the analysis has been done for the yearly data. Second generation panel unit root test has been employed in this study and in this way, cross-sectional dependence has been considered. Since non-stationarity exists in variables, cointegration tests are also employed while controlling CD at the same time. FMOLS, DOLS and SGMM estimation techniques have been employed due the fact that cointegration association among variables was there. Hence the estimators were long-run cointegration parameters.

This study results show that Economic complexity has a significant and positive relationship with EF. Contrary to that, renewable energy generation has a significant negative relationship. Moreover, Economic growth, urbanization, export quality and trade show positive association while human capital is found negatively and significantly related with EF. The positive impact of economic complexity, as well as export quality on EF, is a key lesson for policymakers in the leading ECI as well as developing countries to consider product quality as one of the determining factors to formulate environmental laws and policies (Shahzad et al., 2021a, b; Ulucak & Bilgili, 2018).

This study concludes that more clean and renewable energy sources are very helpful in mitigating ecological footprint and thus solving the global pollution problem. Such conclusions lead us toward the possible interaction between SDG-7-Affordable and Clean Energy and measures to mitigate ecological footprints. Hence non-renewable energy sources are the key role players in further improving export product quality and controlling environmental degradation. Empirical results of this study further reiterate that in determining income levels and overall energy consumption in developed and developing countries, economic complexity and export quality has a very important role to play. Taking policy lessons from these results, developing countries should adopt policies that can guide their energy sector toward transformation and environmental sustainability.

Future research can incorporate more explanatory variables, and data of other regions can be analyzed too. Moreover, researchers can contribute to the economic complexity literature by further extending this ECI-EF framework with DEA (Data envelopment analysis) model. Large-sized data and other variables, for example institutions can be used too.

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**Declarations**

**Conflict of interest** The authors declare that they do not have any conflict of interest.

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