



# Dynamic relationship between technological innovations, financial development, renewable energy, and ecological footprint: fresh insights based on the STIRPAT model for Asia Pacific Economic Cooperation countries

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## Abstract

This article seeks to analyze the impact of technological innovations, financial development, renewable energy consumption, economic growth, and population on the ecological footprint in Asia Pacific Economic Cooperation (APEC) countries by utilizing the balanced longitudinal data set during the period from 1990 to 2017. This study creates a new technological innovation index through principle component analysis including three important indicators that represent the technology and employs a consistent environmental framework identified as Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model. The second generation panel estimation technique is employed to calculate robust and reliable outcomes. After confirming the cross-sectional dependency among series, panel unit root tests confirm that all variables are stationary at their first integrated order. Furthermore, Westerlund cointegration test confirms the presence of long-run association among variables. The outcomes explore that financial development and renewable energy utilization significantly accelerate the environmental quality by 0.0927% and 0.4274%, respectively. While, the increase in technological innovation activities, economic growth, and population size has a detrimental effect on environmental quality in the long run by 0.099%, 0.517%, and 0.458%, respectively. Moreover, the results of panel Dumitrescu and Hurlin (D-H) non-causality test discovered the bidirectional causality relationship between financial development, technological innovations, renewable energy consumption, economic growth, and population size with the ecological footprint. These empirical findings provide some vital policy implications for central authority and policymakers to overcome the detrimental impact on environmental quality in the APEC region.

**Keywords** Technological innovations · Financial development · STIRPAT model · FGLS estimator · APEC countries

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## Introduction

It is observed that there is a strong relationship between the changes in world temperature and aggregate pollution level. Indeed, since the mid-twenty century, there is a high probability that human activities generate greenhouse gases (GHGs) that turn to increase the noticeable global temperature. Carbon dioxide (CO<sub>2</sub>) emissions comprise an approximated 75% of world pollution due to more combustion of conventional energy utilization (Ganda 2019). Since 1750 occurred in the last 40 years, human activities are more responsive to increase the CO<sub>2</sub> emissions and primary energy utilization generates it up to 2/3 of global pollution level (OECD 2016). On the other hand, human-induced agricultural activities generate nitrous oxide (N<sub>2</sub>O) and methane gas that is also causing more GHGs emissions in the environment (Chandio et al. 2020a). To

overcome such kind of global pollution, it is a dire requirement in more intensive policy to curtail the CO<sub>2</sub> emission and increase the level of investment in research and development programs, technological innovations, development in the financial sector, and energy markets.

It is analyzed that improved and efficient use of technology and innovations play a vital role in order to expand in green economies and curb the CO<sub>2</sub> emission. The advancement in the utilization of renewable energy sources, hybrid technology, and electric vehicles already has guided to more reduction in residual material and pollution level and being achieved advancement in hydrogen cars, organic photovoltaics, and biofuel energy (Burston 2016). This infers that soundness and improvement in technology and innovation level of the economy imply the efficient prospects of expansion in renewable sources and green economies.

In recent years, innovation and its relationships with the environmental problem have drawn significant attention to several researchers and academics all over the world. The innovation activities can be defined as the execution of a modern and significantly better product (goods and services), or process, a new marketing system or modern organization technique in business activities, workplace organization, or peripheral relations. The minimum requirement for an innovation is that the production process, marketing method must be new (or significantly improved to the firm) (OECD 2005). In this regard, several studies examined that innovation activities improve the environmental quality (Huang et al. 2020a; Churchill et al. 2019). While, other studies conclude that innovation activities have a detrimental effect on environmental quality (Ganda 2019; Dauda et al. 2019). According to the Intergovernmental Panel on Climate Change report (IPCC 2018), the number of anthropogenic emissions in the air can be reduced by the adoption of technological innovation measures and environmental policies. Likewise, the discussion on innovation measures was at the center of the debate. However, the most used and developed indicators are research and development (R&D) activities and patent applications (Greenhalgh and Rogers 2010). Technological innovation is the key factor in this empirical nexus that can contribute to transforming from conventional to more efficient and sustainable energy resources such as renewables (Andreoni and Levinson 2001; Alvarez-Herranz et al. 2017). Although, Torras and Boyce (1998) stated: “There is no a priori reason to assume the relationship between income and environmental quality to be strictly monotonic.” However, in moderating this linkage, the current study commencing the role of technological innovations would be justifiable to the fact that the association between environmental degradation and its drivers can be reasonable by innovations. More importantly, the world pollution control strategy is intimately connected to energy innovations (Herring and Roy 2007; Kahouli 2018). In order to examine

these hypothetical prospects, the current article contains a center of attention to the concern of technological innovations that help to control the emission level. In concluding, technological innovations are instinctively more significant and appropriate for environmental degradation.

Financial development is another important indicator of the development and sustainability of the economy as well as environmental quality, especially in emerging economies. It is more evident to reflect the environmental concerns of the financial development sector. More specifically, the development of the financial sector can play an important role to protect environmental quality. In pursuit of these concerns, several studies found that developed financial sector enhances environmental degradation (Sadorsky 2010; Zhang 2011; Huang and Zhao 2018; Ehigiamusoe and Lean 2019; Saud et al. 2020). Contrarily, the developed financial sector could overcome the pollution level, when it allows firms to adopt and utilize modern and advanced cleaner technologies and energy efficiency and promotes investment in eco-friendly projects (Ehigiamusoe and Lean 2019). Furthermore, there are three ways that elucidate the relationship between financial development and environmental degradation. (i) Theoretically, it is reasonable to increase the level of foreign direct investment (FDI) in the domestic country that required more energy to produce goods in turn to accelerate the emission level. (ii) The vendor install modern capital and initiate new projects after stock and financial market development that cause to utilize more energy use and generate carbon emissions. (iii) In the development process of every economy will lead to producing more luxury goods such as air conditioners, refrigerators, automobiles, and other many electronic products which consume more energy sources resulting from increasing the carbon emissions (Usman et al. 2020a). In contrast, many other studies showed that financial development overcomes environmental degradation (Ibrahiem 2020; Nathaniel et al. 2019; Ehigiamusoe et al. 2019). However, Taher (2020) recommended investing in technology and environment-friendly production through financial development, which will reduce CO<sub>2</sub> emissions. Besides, clean and renewable energy consumption plays a vital role in the environmental problem, and many countries have increasingly adopted the sources of such kinds of energies from the previous few decades. Some findings suggested that clean energy consumption improves environmental issues (Dogan and Seker 2016; Cai et al. 2018; Khalid et al. 2020; Usman et al. 2020a), while other studies found a positive effect of carbon emissions (Destek and Sinha 2020). However, Ehigiamusoe et al. (2019) provided another evidence to accelerate environmental quality through banking sector development while stock markets do not enhance the environmental quality. Based on these different findings, more investigations should be required to explain this relationship. Accordingly, this paper examines the impact of technological innovation, financial

development, and renewable energy utilization on environmental damages.

Literature broadly discussed the proxies of environmental problems. Therefore, plenty of investigations have regularly utilized CO<sub>2</sub> emissions as a measure of environmental impacts (Han et al. 2020; Sinha et al. 2020). However, CO<sub>2</sub> emissions represent over 70% of greenhouse gas emissions universally and are viewed as one of the principal drives of global warming (Yilanci and Pata 2020). However, it may prove as a weak indicator (Ulucak and Apergis 2018). In this regard, the current study takes into account the ecological footprint (EFP) as a more comprehensive measure of the environmental problem because it addresses the main industrial and other human activities that contribute to increasing the environmental degradation (Li et al. 2017). To the best of our knowledge, the majority of the previous literature has employed the single environmental factor such as CO<sub>2</sub> emissions as a proxy of environmental damages; however, it is commonly observed that human activities not only affect the ecological atmosphere but also it deteriorates the land and water quality; thus, it is dire requirement to use a comprehensive indicator that represents the whole factors of environmental degradation. Moreover, the ecological footprint variable is an accounting instrument use to approximate how much water and land area is needed to produce all goods consumed and to absorb the wastes material generated by individuals and other sectors (Wang and Dong 2019; Dias De Oliveira et al. 2005; Khalid et al. 2020). However, CO<sub>2</sub> emission is only part of the ecological footprint. Since the seminal work of Rees (1992) and Wackernagel and Rees (1996), the ecological footprint is widely used to measure environmental quality, which was defined as an apparatus expected to follow human necessities on the biosphere's regenerative limit and human reliance on the environment. Hence, EFP represents the extent to which humans exceed the limit environmentally. In other words, EFP determines how much inhabitants of our planet consume natural resources to guarantee their demands and requirements. It is a tool of comparison between activities and their influences on the environment and natural resources (Belčáková et al. 2017). Over the past 50 years, the ecological footprint has risen at a faster pace than world biocapacity. With the consumption of natural resources such as energy, water, and land, our ecological footprint has expanded by around about 190%. Based on these arguments, it is necessary to study this measure and the influence of technological innovation and other control variables.

Several studies have often scrutinized the relationship between innovation and environmental quality such as in OECD countries (Ganda 2019), for G7 countries (Churchill et al. 2019), for next 11 countries (Sinha et al. 2020), and the BRICS countries (Khattak et al. 2020) with other explanatory variables. However, to the best of our knowledge, there is no study to analyze this relationship in the STIRPAT framework

for Asia Pacific Economic Cooperation (APEC) simultaneously. To do this, we select the APEC countries panel. APEC countries capture 57% of the world economic growth, and the electricity utilization accounts for 60% of global electricity use, while these countries hold the share of trade in this region is approximately 47% of world traded commodities (Zaidi et al. 2019). Thus, their policies might be influenced by several APEC group of these economies which illustrated that these countries are enhancing their FDI through trade in which turn to increase the pollution level (Le et al. 2017). These countries have experienced extensive economic growth by utilizing the development of technological innovation, as it appears from their economic development process. The economic interdependence of APEC economies has increased their living standard through foreign direct investment (Zaidi et al. 2019). Therefore, considerable transformations in the resources of energy utilization take place when technological innovation acquires effect in a particular economy. Thus, these statistics attract our attention to select the APEC countries. Moreover, no previous studies have investigated the impact of technological innovations, financial development, and renewable energy on the ecological footprint simultaneously for APEC countries.

The ecological footprint connects with the development of financial sector, and technological innovation has attained more consideration in the field of research. For example, in APEC countries, Zaidi et al. (2019) scrutinized the EKC hypothesis, but they did not test the role of technological innovations and renewable energy utilization in environmental degradation. Similarly, Magazzino (2017) analyzed the long-run association between economic growth, primary energy utilization, and carbon emission by applying the vector autoregressive (VAR) model and observed that there is no long-run relationship exists among these variables. Likewise, Yang et al. (2020a) inspected the nexus of fossil fuel and renewable energy to mitigate carbon emission through environment-biased technological development. However, they did not apply the ecological footprint indicator and the STIRPAT model framework. The advantages and weakness of financial development and technological innovations in APEC region economies should be investigated, specifically from environmental expects (ecological footprint), as knowing the impact of technological innovations on economic growth and environmental degradation, these economies may change their financial structure, enhancement in research and development expenditure, trade and environmental policies to make sure sustainability in their economic growth process. In addition, this study utilizes the new and comprehensive financial development index as measured on the basis of the comparative ranking of world economies on the basis of their financial institutions and market access, depth, and their efficiency. This comprehensive financial development index is based on a complex and multidimensional quality of financial

progression. Moreover, the current study applied the new technological innovation index of three key indicators of research and development, such as trademark applications, patent applications, and technical cooperation grants. The key motives for using these indices are that focusing only on either restricted (local) or overall (global) financial indicators might not depict the true picture of the financial development sector in these nations. On the other hand, due to the various development stages of the economy, the R&D level in these economies fluctuates largely, and consequently, choosing the one single indicator of R&D might not portray an accurate picture of technological innovation and development in APEC countries. In a turn of methodological concerns, previous studies employed the conventional methodology (first generation) that is unable to counter the problem of cross-sectional dependency and slope heterogeneity. However, this study investigates the dynamic relationship by applying the modern (second generation) methodology such as unit root tests, Westerlund cointegration test for detection of a cointegration order, and long-run relationship among variables. In order to investigate the magnitude of long-run coefficients, we applied the feasible generalized least square (FGLS), augmented mean group estimator (AMG), and common correlated effect mean group (CCEMG) estimation approaches, and finally, Dumitrescu and Hurlin panel non-causality test is applied to check the causality relationship flow from one variable to another.

The remaining sections of this paper are organized as follows: Section 2 provides a comprehensive literature review that focuses on the effect of technological innovation, financial development, and renewable energy consumption on ecological footprint. Section 2 expresses the data, variables, and econometric procedures of the current study. In Section 4, the results and their interpretation are discussed. Finally, Section 5 shows the conclusion and corresponding policy recommendations.

## Literature review

The topic of environmental degradation has inspired an extensive amount of studies among several techniques of estimation, including a panel data analysis as well as time series analysis. However, a vast literature used the CO<sub>2</sub> emission as a proxy of environmental deficit against ecological footprint. For this purpose, the literature review is divided into three strands. First strand of this study is based on the linkages between technological progression and environmental degradation. The second strand of this section depends on the dynamic nexus between financial development and environmental damages and finally, the third segment of this section presents the empirical nexus between the utilization of renewable energy and environmental quality.

## Environmental degradation and technological innovation

In recent years, a plethora of research focuses on the effects of technological innovation on environmental degradation by using the different measures of technological innovations. According to Greenhalgh and Rogers (2010), R&D acts, and the patent is measured as input and output, respectively. However, R&D activities show many drawbacks. One of the most popular disadvantages is the data availability of such indicators. Thus, the developed countries have a more efficient system to collect data on R&D investment than the other countries. In addition, only the extent of R&D expenditures will be eventually changed to innovations outputs (Greenhalgh and Rogers 2010). Based on these arguments, we used the number of trademarks and patents as a proxy of technological innovation.

Nevertheless, several researchers observed that investment in R&D improves environmental quality. For instance, Huang et al. (2020b) analyzed the influence of technological innovation on carbon intensity in the case of China. The results showed that the effect depends on the R&D activities at various phases and actors implemented. Besides, the R&D activities at third stages and industrial enterprises have a significant positive role in reducing the carbon intensity. Similarly, Zhang et al. (2017) found that environmental innovation measures (energy efficiency and resources for innovation and knowledge innovation) reduce carbon emission effectively in China. Another study proposed by Churchill et al. (2019) studied the linkages between R&D intensity and CO<sub>2</sub> emissions during the period from 1870 to 2014 in G7 countries. They found a different effect of technological innovation on carbon emissions. More precisely, R&D activities significantly improve the environmental quality in G7 nations. Furthermore, Ahmad (2019) analyzed the effect of innovation shocks on CO<sub>2</sub> emissions in OECD economies from 1990 to 2014. From multiple empirical analyses, the results show that positive shocks of innovations promote environmental quality. In the next 11 economies, Sinha et al. (2020) investigated the relationships between the effect of technological progression, economic growth, renewable energy consumption, and population on environmental degradation. The findings show that the government should provide more opportunities to create employment prospects through R&D activities in order to improve environmental quality. However, Khattak et al. (2020) studied the association between technological innovation, renewable energy, and carbon emissions in BRICS countries from 1980 to 2016. The outcomes explored that there is a positive association between innovation activities and CO<sub>2</sub> emissions in China, Russia, India, and South Africa. Likewise, the empirical results of Ibrahiem (2020) explored that innovation and alternative energy resources enhance the environmental

quality in Egypt over the period from 1971 to 2014. Youssef (2020) examined the relationship between residential and non-resident patents, renewable energy, carbon emissions, and economic growth from 1980 to 2016 for the USA. The results revealed that the non-resident patents enhance the environmental quality. However, resident patents increase carbon emissions in the USA. Likewise, Ganda (2019) studied the relationships between innovations and CO<sub>2</sub> emission in OECD economies from 2000 to 2014. The results indicated a positive and significant effect between triadic patent families, while the impact of the investment of R&D is negative and significant on carbon emission. In contrast, Cheng et al. (2019) examined the association between economic growth, clean energy, patent applications, and carbon emissions from 2000 to 2013 in OECD member countries. Using a panel quantile regression, the findings indicated a positive but insignificant effect of innovation on environmental quality. Moreover, Dauda (2019) studied the influence of innovation and economic growth on CO<sub>2</sub> emissions for developed and developing countries. The outcomes revealed that the effect of innovation on carbon emissions differs from one region to another; thus, innovation improves environment quality in G7 countries, while it leads to increase CO<sub>2</sub> emissions in MENA and the BRICS countries.

### Environmental degradation and financial development

The empirical literature on financial development and its relation to the environmental impact has been at the center of the intention of many researchers from all over the world. In this line, Tamazian et al. (2009) examined the effect of financial development on environmental degradation in BRICS countries during the period from 1992 to 2004. The results showed that financial development is responsible for reducing carbon emissions. In China, Jalil and Feridun (2011) found that financial development accelerates environmental quality from 1953 to 2006. Aye and Edoja (2017) discovered a two-way causal relationship exists between CO<sub>2</sub> emission and financial development during the period from 1970 to 2013 in 31 developing countries. More recently, Ehigiamusoe (2020a) examined that sound, and developed financial sector auspiciously moderates the effect of energy utilization on CO<sub>2</sub> emissions in the Association of Southeast Asia Nations (ASEAN) countries. Conversely, financial development harmfully moderates the effect on environmental degradation in ASEAN and China's economy. Salahuddin et al. (2018) employed the autoregressive distributed lag (ARDL) technique in Kuwait from 1980 to 2013. The outcomes explored the positive and significant impact of financial development on CO<sub>2</sub> emissions in the case of Kuwait. Similarly, Nathaniel et al. (2019) analyzed that economic growth and financial development lead to deteriorating

the environmental quality in the long run from 1965 to 2014 in the case of South Africa. Likewise, Ibrahiem (2020) proved that financial development deteriorates environmental quality in Egypt. In another study, Zaidi et al. (2019) indicated that globalization and financial development diminish CO<sub>2</sub> emissions in APEC countries from 1990 to 2016. On contrarily, Saud et al. (2020) examined the effect of globalization and financial development on the environment in BRI countries from 1990 to 2014. The findings underlined the pollution increase due to growth in financial development. Destek and Sarkodie (2019) explored the relationship between financial development, economic growth, energy consumption, and EFP in 11 newly industrialized economies from 1977 to 2013. The results indicated that there is an adverse relationship between financial development and pollution level. In addition, there is a one-way causality from ecological footprint to financial development.

### Environmental degradation and renewable energy consumption

Renewable energy utilization and its link with environmental quality have also been at the center of discussions recently. Several studies suggested that the government should adopt renewable energy consumption in order to attempt sustainable growth. By employing the Bootstrap ARDL approach, Cai et al. (2018) examined the relationship between renewable energy utilization and carbon emissions in G7 economies. They discovered a one-way causality between clean energy consumption and environmental degradation for Germany. However, in the case of USA, a unidirectional causality relationship was discovered from renewable energy consumption to CO<sub>2</sub> emissions. The results suggested that the government should adopt renewable energy in order to attempt sustainable growth. Moreover, Chandio et al. (2020b) examined the association between electricity consumption, FDI, and economic growth covering the period from 1997 to 2017 in the case of Pakistan. The findings revealed that renewable energy is more responsible to diminish pollution and pull in adequate FDI. Similarly, Ito (2017) found that renewable energy reduces carbon emissions in developing countries. For the same objective, Dogan (2016) also recommended encouraging investments in renewable energy consumption in Turkey. Another massive study proposed by Cheng et al. (2019) examined the relationship between economic growth, renewable energy, and carbon emissions from 2000 to 2013 in OECD countries. Empirical results revealed that the EKC hypothesis is confirmed by renewable energy consumption and CO<sub>2</sub> emission. However, Dogan and Seker (2016) analyzed the role of real output, renewable and non-renewable energy consumption on carbon emissions. The results explored that renewable energy consumption diminishes CO<sub>2</sub> emission. Furthermore, Wang and Dong (2019)

analyzed a positive effect between the ecological footprint, GDP growth, non-renewable energy utilization and urbanization, while renewable energy is helpful to enhance the environmental quality for 14 Sub-Saharan Africa nations from 1990 to 2014. In the same line, Destek and Sinha (2020) investigated the connection between trade, renewable and non-renewable energy utilization on the ecological footprint for OECD economies during the period from 1980 to 2014. The results indicated that renewable energy consumption enhances environmental quality while non-renewable energy utilization is more responsible for deteriorating environmental quality. In the same regards, Ehigiamusoe (2020b) examined that utilization of non-renewable electricity has detrimental effects on environmental degradation, while renewable electricity production diminishes CO<sub>2</sub> emissions in the African continent. Furthermore, non-renewable electricity generation from natural gas, coal, and oil has detrimental impacts on environmental degradation while the generation of electricity from hydro sources alleviates environmental damages. Moreover, Sharif et al. (2020) employed similar indicators as used in the study of Destek and Sinha (2020) and found some empirical evidence in the long run from 1965 to 2017 in the case of Turkey, by using Quantile Autoregressive Lagged approach. More precisely, most of the empirical studies found that technological innovation, financial development, and clean energy sources have ability to improve environmental quality. Similarly, Chandio et al. (2020a) examined how crop production, forest, power consumption, and livestock production affect carbon emissions in the case of China from 1990 to 2016. The results explored that carbon emission is adversely affected by the power consumption in the agriculture sector and forest area. However, to the best of our knowledge, the greater part of the published literature incorporates CO<sub>2</sub> emissions as an indicator of environmental degradation, while very few investigations adopted ecological footprint as a measure. For this purpose, we adopt the role of technological innovation, financial development, and renewable energy consumption in the ecological footprint for APEC economies.

## Theoretical model, data, and empirical methodology

### Theoretical model and data

The current study intends to scrutinize the impact of technological innovation, financial development, economic growth, renewable energy consumption, and population on the ecological footprint for the Asian Pacific Economic Cooperation (APEC) countries over the period from 1990 to 2017. In order to investigate the impact of concerned variables, we have pondered the IPAT ( $I = PAT$ ) structure as proposed by Ehrlich and Holdren (1971). They also highlighted the three important

factors that affect environmental quality. This study investigates the standardized literature accordance with the IPAT framework to estimate the mathematical form of our empirical model is expressed as follows:

$$EFP_{it} = f(FD_{it}, TECH_{it}, GDP_{it}, REC_{it}, POP_{it}) \quad (1)$$

Where, EFP is ecological footprint, FD refers to financial development index, TECH shows the index of technological innovations, GDP denotes the per capita gross domestic product, REC denotes the renewable energy consumption, and POP shows the total population size,  $i$  indicates the individual countries ( $i = 1, 2, 3, \dots, N$ ), and  $t$  denotes the study time dimension ( $t = 1, 2, 3, \dots, T$ ). In order to construct the technological innovation index, principal component analysis (PCA)<sup>1</sup> was applied by considering three major research and development indicator accordance with Sinha et al. (2020).

- (i) Total numbers of patent applications (direct and PCT national phase entries)
- (ii) Total number of trademark applications (direct and via the Madrid system)
- (iii) Total grant for direct applications (US dollars)

$$TECH_{it} = \theta_{0it} + \theta_{1it}PAT_{it} + \theta_{2it}TMA_{it} + \theta_{3it}GRA_{it} + \mu_{it} \quad (2)$$

The principal component analysis (PCA) technique is employed to transform otherwise highly correlated indicators into lesser uncorrelated indicators, known as principal components. The major concern to select these indicators for PCA is that every country has a difference in their economic growth, research expenditure, and development level. Therefore, a single indicator of R&D might not describe the actual scenario of technological progression and innovations in these under-examined countries.

After converting the technological progression index, we gaze reverse at the IPAT structure of Eq. 1 where the impact of environmental quality (I) is related to the total population (P), Affluence (A) related to the level of economic activities, and technological progression level (T). The way to analyze the influence of these three factors on environmental quality is to change one factor, and others remain fixed. The crucial constraint on the IPAT model is the influence of all variables on the environmental quality is described as a constant fraction Fan et al. (2006). To analyze the impact of these aforementioned variables on the environment, Dietz and Rosa (1994) developed the stochastic effects by regression on Population, Affluence level, and Technological progression (STIRPAT) model by reconstructing the IPAT model. This revised model can be written as follows:

<sup>1</sup> Findings of principal component analysis are available on request.

$$I_{it} = K P_{it}^\alpha A_{it}^\beta T_{it}^\gamma \varepsilon_{it} \tag{3}$$

To eradicate the constraints of fixed proportional, we include  $\alpha$ ,  $\beta$ , and  $\gamma$  are the coefficients of  $P$ ,  $A$ , and  $T$  in IPAT model. Whereas,  $K$  and  $\varepsilon$  represent the intercept and contemporaneous error term and the subscripts  $i$  and  $t$  refer to individual cross-section and time dimension, respectively. The logarithmic form of Eq. 1 can be defined as follows (Lin et al. 2017):

$$\ln I_{it} = K_i + \alpha(\ln P_{it}) + \beta(\ln A_{it}) + \gamma(\ln T_{it}) + \varepsilon_{it} \tag{4}$$

This IPAT Equation is developed in the logarithmic form to explore the impact of population, GDP and technological innovation on environmental quality. Our empirical model, as shown in Eq. 1, is constructed similarly in line with this structure. Where EFP is an ecological footprint (proxy for environmental degradation), POP is reflected as population; GDP, REC, and FD are the proxy of economic activities; and TECH shows the technological innovation index.

The current study uses annual data during the time span from 1990 to 2017 for 16 APEC countries, named as Australia, Canada, Chile, China, Japan, Malaysia, Mexico, New Zealand, Peru, Philippines, Russia, Singapore, South Korea, Thailand, USA, and Vietnam. We exclude some countries due to non-availability of data like Brunei Darussalam, Indonesia, Hong Kong, and Papua New Guinea. The data of technological innovation variables are taken from the World Intellectual Property Organization (WIPO 2019); financial development index data is extracted from the International Monetary Fund (IMF 2019). This index is based on the nation’s relative ranking regarding their depth, access, and efficiency of both particular financial markets and institutions (IMF 2019). This financial development index is relying on between 0 and 1, but we convert it into zero to one hundred in order to compose it compatible with under-examined variables. The data of ecological footprint (Global hectares per person) is obtained from global footprint network (GFPN 2019) and finally, economic growth (constant 2010 US Billions dollars), renewable energy utilization (% of total final energy use), and population (total population) data are extracted from world development indicators (WDI 2019). In order to overcome the problem of heteroscedasticity and sharpness of data, we take the natural logarithm of Eq. 1 that can be written as follows:

$$\begin{aligned} \ln(\text{EFP}_{it}) = & \Phi_{0it} + \Phi_{1it}\ln(\text{TECH}_{it}) + \Phi_{2it}\ln(\text{FD}_{it}) \\ & + \Phi_{3it}\ln(\text{GDP}_{it}) + \Phi_{4it}\ln(\text{REC}_{it}) \\ & + \Phi_{5it}\ln(\text{POP}_{it}) + \mu_{it} \end{aligned} \tag{5}$$

Where  $\Phi_0$  represents the individual intercept term;  $\Phi_1, \Phi_2, \Phi_3, \Phi_4, \Phi_5$  express the elasticity of explanatory variables;

$\ln\text{EFP}$ ,  $\ln\text{TECH}$ ,  $\ln\text{FD}$ ,  $\ln\text{GDP}$ ,  $\ln\text{REC}$ , and  $\ln\text{POP}$  show the natural logarithmic transformation of ecological footprint, technological innovations, financial development, economic growth, renewable energy utilization, and population size; and  $\mu_{it}$  refers to the stochastic error term.

Table 1 reports the descriptive statistics and correlation matrix of analyzed variables. It confirms that ecological footprint in APEC countries has a mean value of 4.580732 global hectares per capita with a minimum value of 0.712321, and maximum value of 10.48166. This exposes that a significant disparities exist in ecological footprint across APEC countries. While the ecological footprint is a very crucial problem in some APEC countries; however, it is not serious in some other countries as depicted by maximum and minimum values. Financial development index ranges from the maximum value of 95.20200 to the minimum value of 0.012662, with mean value of 54.02570. The value of standard deviation is also very high that portrays while some APEC countries have been capable to build their financial markets and institutions, some other countries are still in the under-development stage. Referring to the technological innovation index, APEC countries have the mean value of 69,341.68, with a large standard variation of 159,000. This denotes that the technological innovation varies significantly across APEC countries. Similar features were analyzed for economic growth that depicts a mean value of 1844.465 US billion dollars and in case of renewable energy utilization, the mean value of 17.92752, with a standard deviation of 15.21404. Finally, Table 1 also depicts the same attributes for population, the mean value of 147.0541, with a standard deviation of 301.8659. The values of the standard deviation of all variables are very high. This implies that the points of data values are very far from their average values, indicating that the high possibilities of heterogeneity across cross-sections for under-examined variables.

The bivariate correlation matrixes for all concerned variables are also reported in Table 1. The ecological footprint is high and positively correlated with financial development and adversely with renewable energy utilization, followed by technological innovations, economic growth, and population. In addition, renewable energy utilization is negatively correlated with all variables except population. However, economic growth and population size are highly and positively correlated with technological innovations.

### Empirical methodology

#### Cross-sectional dependency tests

One key issue in estimation of panel data analysis is the presence of cross-sectional dependency (CSD) that can cause

**Table 1** Descriptive statistics and bivariate correlation analysis

	EFP	FD	TECH	GDP	REC	POP
Mean	4.580732	54.02570	69,341.68	1844.465	17.92752	147.0541
Median	4.282561	52.90830	18,130.99	404.1070	12.81639	54.01219
Maximum	10.48166	95.20200	1,542,692.0	17,348.63	76.08164	1386.395
Minimum	0.712321	0.012662	1446.807	29.45848	0.194834	3.047132
Std. Dev.	2.567761	21.12644	159,000.4	3439.979	15.21404	301.8659
Skewness	0.456456	0.092657	5.726560	2.754971	0.958760	3.324976
Kurtosis	2.194979	1.979321	43.59681	10.16298	3.929330	12.78715
No. of Obs.	448	448	448	448	448	448
EFP	1.000					
FD	0.748669*	1.000				
	[23.84956]					
TECH	0.143704*	0.261844*	1.000			
	[3.066671]	[5.729611]				
GDP	0.473887*	0.454104*	0.639788*	1.000		
	[11.36504]	[10.76390]	[17.58046]			
REC	-0.570646*	-0.588595*	-0.210925*	-0.319655*	1.000	
	[-14.67532]	[-15.37599]	[-4.556980]	[-6.124506]		
POP	-0.138466*	-0.550488**	0.645689*	0.369816*	0.133858*	1.000
	[-2.952673]	[-2.723576]	[17.85767]	[8.405975]	[3.989911]	

\* and \*\* signify 1% and 5% level of significance and *t*-statistics are presented in [ ]

inefficient and inconsistent in estimated coefficients, and therefore error term dependency should be tested to eliminate this problem. The CSD can take place due to omitted common effects, common shocks, spatial effects, externalities, and unobserved or latent components (De-Hoyos and Sarafidis 2006). Testing for CSD plays a crucial step in deciding the suitable panel unit root tests. To do this, before testing to panel stationary tests, initially this study utilizing the several CSD tests to check the existence of CSD across cross-sections and variables. In order to check the CSD in variables, this study utilized the Pesaran CD test (Pesaran 2004), Breusch-Pagan LM test (Breusch and Pagan 1980), Pesaran Scaled LM test (Pesaran 2004), and Bias-Corrected Scale LM (Baltagi et al. 2012). The null hypothesis (*H*<sub>0</sub>) of CSD test is presenting as follows:

$$H_0 : \eta_{ij} = corr(\varepsilon_{it}, \varepsilon_{jt}) = 0 \forall i \neq j \tag{6}$$

The (Pesaran 2004) CSD test is represented as follows:

$$CSD = \sqrt{\frac{2T}{n(n-1)}} \left( \sum_{i=1}^{n-1} \sum_{k=i+1}^n \hat{\eta}_{ik} \right) \sim n(0, 1) \quad i, k \tag{7}$$

$$CSD = (1, 2, 3, \dots, 50, \dots, N)$$

$$R = \sqrt{\frac{2T}{n(n-1)}} \left( \sum_{i=1}^{n-1} \sum_{k=i+1}^n \hat{\eta}_{ik} \right) \left[ \frac{(T-j)\hat{\eta}_{ik}^2 - (T-j)\hat{\eta}_{ik}^2}{Var(T-j)\hat{\eta}_{ik}^2} \right] \tag{8}$$

The term  $\hat{\eta}_{ik}^2$  denotes the pairwise correlation in residuals from sample estimates by estimating the simple regression.

**Panel unit root tests**

In the second step of panel data analysis, it is essential to conduct the unit root tests to determine the order of stationarity of concerned variables. Thus, panel unit root tests can be applied to achieve this purpose. As, in the existence of CSD and slope heterogeneity, first generation unit root tests cannot be employed due to over rejection of null hypothesis and poor size property in which turn to produce misleading information about cointegration order. Therefore, we applied second generation unit root tests that allowing the CSD across cross-sections in heterogeneous panels. For these reasons, Pesaran (2007) proposed two second generation panel unit root tests such as cross-sectional augmented Dickey Fuller (CADF) and cross-sectional augmented Im Pesaran and Shin (CIPS) (Breitung and Das 2005) are applied. The functional form of CADF test statistics is denoted as follows:

$$\Delta Y_{it} = \pi_i + \theta_i y_{i,t-1} + \gamma_i \bar{y}_{t-1} + \Psi_i \Delta \bar{y}_t + \mu_{it} \tag{9}$$

Putting the lag term in Eq. 9 results the subsequent Eq. 10 is calculated as follows:

$$\Delta Y_{it} = \pi_i + \theta_i y_{i,t-1} + \gamma_i \bar{y}_{t-1} + \sum_{j=0}^p \Psi_{ij} \Delta \bar{y}_{t-j} + \sum_{j=1}^p \delta_{ij} \Delta y_{i,t-j} + \mu_{it} \tag{10}$$

Where  $\bar{y}_{t-j}$  and  $\Delta y_{i,t-j}$  show lagged level averages and the first difference operator of each cross-section. The CIPS panel unit root test is expressed in Eq. 11 as follows:



$$CIPS = N^{-1} \sum_{i=1}^N \theta_i(N, T) \tag{11}$$

Where the parameter  $\theta_i(N, T)$  refers to CADF statistics that can be replaced as:

$$CIPS = N^{-1} \sum_{i=1}^N CADF_i \tag{12}$$

**Westerlund cointegration test**

After confirmation of the stationarity shocks, next step of panel data analysis is testing the long-run cointegration among series. Considering both CSD and heterogeneity issues, we required second generation panel cointegration tests which provide accurate and reliable information about long-run cointegration relationship among variables. In order to address the CSD and heterogeneity issue, Westerlund (2007) developed a structure dynamic based error correction panel cointegration test that counters both issues in panel data analysis. The null hypothesis of Westerlund cointegration test is the absence of long-run cointegration among variables against the alternative hypothesis that shows the presence of long-run association among variables. Westerlund cointegration test is calculated as follows:

$$\Delta X_{i,t} = \Psi' d_i + \Phi_i (X_{i,t-1} - \pi' Y_{i,t-1}) + \sum_{j=1}^q \Phi_{i,j} \Delta X_{i,t-j} + \sum_{j=0}^q \eta_{i,j} \Delta Y_{i,t-j} + \varepsilon_{i,t} \tag{13}$$

Where  $\Phi_i$  denotes the adjustment speed which corrects the system back to equilibrium.

**Long-run elasticity regression tests**

**Parks feasible generalized least square** Reed and Ye (2011) proposed the feasible generalized least square (FGLS) estimator that is more appropriate in the presence of CSD, serial correlation, and heteroscedasticity problem in the panel. This estimation approach is well more suitable in the condition of time dimension that is relatively greater than cross-sections ( $T > N$ ) in the panel (Usman et al. 2020b). The FGLS estimator is expressed in Eq. 14 as follows:

$$\hat{\theta} = \left( Z' \hat{\Omega}^{-1} Z \right)^{-1} Z' \hat{\Omega}^{-1} M \tag{14}$$

$$var(\hat{\theta}) = \left( Z' \hat{\Omega}^{-1} Z \right)^{-1} \tag{15}$$

Where the term  $\hat{\Omega}$  contains the robustness about CSD, serial correlation, and heteroscedasticity.

**Augmented Mean Group estimator** Wang and Dong (2019) and Usman et al. (2020b) revealed that first-generation estimation tests are unable to capture the effect of possible cross-sectional dependency and slope heterogeneity in the panel data set. In order to address the problem of CSD and heterogeneity, it is more useful to employ the Augmented Mean Group (AMG) estimator proposed by Eberhardt and Bond (2009). AMG approach also captures the CSD problem by incorporating the coefficient of common dynamic effect. In this regards, the AMG estimation approach involved two-stage AMG methods (Usman et al. 2020b).

AMG First-Stage:

$$\Delta Y_{it} = \alpha_i + \beta_i \Delta Z_{it} + \gamma_i G_t + \sum_{t=2}^T \Psi_i \Delta F_t + \mu_{it} \tag{16}$$

AMG Second-Stage:

$$\hat{\beta}_{AMG} = N^{-1} \sum_{i=1}^N \hat{\beta}_i \tag{17}$$

Where  $\Delta$  indicates the operator of first difference;  $Y_{it}$  and  $Z_{it}$  indicate the dependent and explanatory variables;  $\alpha_i$  shows the intercept term of individual cross-section;  $\beta_i$  indicates the coefficients of the specific country;  $G_t$  denotes the unobserved (latent) common factor with heterogeneous dynamic;  $\Psi_i$  indicates the time dummy coefficient (dynamic common process);  $\hat{\beta}_{AMG}$  denotes that AMG estimator for mean group, and finally the term  $\mu_{it}$  represents the stochastic error term.

**Common Correlated Effect Mean Group estimator**

Salahuddin et al. (2020) reported that Common Correlated Effect Mean Group (CCEMG) estimation approach produces robust and reliable coefficient in the presence of CSD and slope heterogeneity. It allows the parameter of heterogeneous slope across individual cross-section by taking the mean of every particular country's elasticity. While the AMG approach captures the unobserved common factor in the model. The mathematical form of CCEMG approach is expressed as follows:

$$\Delta Y_{it} = \alpha_{1i} + \beta_i Z_{it} + \Phi_i \bar{Y}_{it} + \eta_i \bar{Z}_{it} + \pi_i W_t + \mu_{it} \tag{18}$$

Where,  $Y_{it}$  and  $Z_{it}$  show the observables,  $\beta_i$  represents each unit slope,  $\alpha_i$  shows the heterogeneous constant factor of an individual unit,  $W_t$  shows the unobserved common factors, and  $\mu_{it}$  indicates the random error term.

$$CCEMG = \frac{1}{N} \left( \sum_{i=1}^n \hat{\eta}_i \right) \tag{19}$$

Where,  $\hat{\eta}_i$  the term shows the individual cross-sectional coefficient estimated from Eq. 18.

**Panel Dumitrescu and Hurlin (D-H) non-causality test**

It is better to discover the causality direction when the long-run association of the series exists in panel data analysis. Dumitrescu and Hurlin (2012) proposed a granger non-causality test to check the causality direction in heterogeneous panels. The important advantages of this test are that it accounts for CSD and slope heterogeneity. There are also other several reasons to employ this test is that initially, the implementation of this test is very simple, using the Monte Carlo simulation, this test performs very well even small data property ( $T < N$ ), this test do not need to require any estimation of the individual panel and finally, this test can be executed in both unbalanced and balanced panels.

D-H causality test is represented as in the following linear functional form:

$$Y_{it} = \beta_i + \sum_{k=1}^q \delta_i^k Y_{i,t-k} + \sum_{k=1}^q \eta_i^k X_{i,t-k} + \mu_{it} \tag{20}$$

Where  $Y$  and  $X$  are two variables that follow the stationarity property for particular cross-sections in  $T$  time periods. The parameters  $\beta_i$  and  $\eta_i = (\eta_i^1, \eta_i^2, \eta_i^3, \dots, \eta_i^k)$  are assumed to be fixed in all time periods. The null ( $H_0$ ) and alternative ( $H_1$ ) hypothesis is represented as follows:

$$H_0 : \eta_i = 0 \quad \text{for } \forall i \tag{21}$$

$$H_1 : \left\{ \begin{array}{ll} \eta_i = 0 & \text{for all } i=1,2,\dots,N_1 \\ \eta_i \neq 0 & \text{for all } i=N_1+1,2,\dots,N \end{array} \right\} \tag{22}$$

Wald test statistics is required to test the  $H_0$  and  $H_1$  hypothesis, which is shown as follows:

$$W_{N,T}^{HNC} = N^{-1} \sum_{i=1}^N W_{i,T} \tag{23}$$

Where  $W_{i,T}$  denotes the individual test of Wald statistics for the unit of the individual cross-section.

**Empirical findings and discussion**

**Results of cross-sectional dependency tests**

This study applied four CSD tests to probe whether the series contain cross-sectional independence or cross-sectional dependence. Table 2 shows the presence of CSD in the variables. This implies that error terms are containing the presence of

unobserved common shocks across cross-section due to economic integration. Therefore, in testing the properties of the stationary process of the variables, second generation panel unit root tests are more appropriate as compared to the first generation. The next process of econometric analysis is to test the stationarity of the aforementioned variables.

**Results of panel unit root tests**

It is observed that most of the economic series are following unit root process resulting of these non-stationary data will lead to inconsistent and biased information. Thus, it is necessary to check the stationary level for concerned variables. In order to calculate the stationarity property of the series, this study used three second-generation panel unit root tests named as Breitung and Das (2005), Pesaran CADF, and CIPS unit root tests as developed by Pesaran (2007). The findings of panel stationary tests are expressed in Table 3 signifying that all variables failed to rejected null hypothesis at level except financial development in both (intercept and constant and trend) form, but it turns to follow the stationarity property at first integrated order I(1). The outcomes of these tests examined that all candidate variables of this research are following the stationarity property, and we can continue with approximating the long-run parameters.

**Results of panel cointegration test**

The very next step of econometric estimation procedure is to perform the cointegration test in order to test the long-run association among series. For this concern, this study applied the Westerlund cointegration tests as CSD tests recommend applying second generation panel cointegration test. The findings from Table 4 explored the existence of cointegration in the panel. It discovered the long-run relationship among the series. The confirmation of cointegration among variables implies that at least one series contains one-way causality relationship (Intisar et al. 2020).

**Results of long-run elasticity estimates**

In order to estimate the long-run relationship among variables, we employed the econometric approaches namely FGLS, AMG, and CCEMG. The empirical results of the ecological footprint function are presented in Table 5. Regarding the connections of technological innovations with an ecological footprint, a 1% increase in technological innovations deteriorates the environmental quality by 0.099% in the long run. This result infers that technological innovations accelerate to enhance the pollution level. Albino et al. (2014) observed that some of the globally developed economies in technological innovations do not always mitigate pollution level as they further progression in technological development. This study

**Table 2** Cross-sectional dependency analysis of the variables

Series	Breusch-Pagan LM		Pesaran Scaled LM		Bias-corrected Scaled		Pesaran CSD	
	Stats.	Prob.	Stats.	Prob.	Stats.	Prob.	Stats.	Prob.
lnEFP	855.725*	0.0000	46.4581*	0.0000	46.1617*	0.0000	5.992*	0.0000
lnTECH	2345.04*	0.0000	142.593*	0.0000	142.296*	0.0000	47.075*	0.0000
lnFD	1795.87*	0.0000	107.144*	0.0000	106.848*	0.0000	41.201*	0.0000
lnGDP	3061.66*	0.0000	188.851*	0.0000	188.554*	0.0000	55.075*	0.0000
lnREC	1155.27*	0.0000	65.7939*	0.0000	65.497*	0.0000	3.625*	0.0000
lnPOP	3098.95*	0.0000	191.257*	0.0000	190.961*	0.0000	42.834*	0.0030

\*indicates a 1% level of significance

utilizes the three important and reasonable indicators of technological innovations that have more influence in these countries with a greater capacity of technological absorption and industrialization (Koçak and Ulucak 2019). The industrialization and human capital accumulation that creates technological development can be linked with the rise in production level; consequently, technological innovation augments environmental damages. Mensah et al. (2019) reported that some technologies that related to energy invention do not accelerate the green growth. The first reason is that these technologies are inadequate in use while others are a few inventions are unable to tackle the well enough environmental issues. One of the major rationales behind this phenomenon is that most of the APEC countries are having the rich in conventional energy sources with low energy prices. One more reason behind this phenomenon is that most of the vendors (inventors) rigorously protect their innovation ideas sharing to other investors (Raiser et al. 2017). Hence,

technological innovations are based on the conventional technologies progression in recent years that encourage the traditional energy utilization sources, which in turn to a high level of environmental pollution. Our results are also consistent with Zhang et al. (2015), Park et al. (2018), Koçak and Ulucak (2019), Churchill et al. (2019), and Chen and Lee (2020).

The association between financial developments with the ecological footprint is statistically significant and adverse in nature. More specifically, 1% influences in financial development will lead to decrease the environmental quality by 0.0927%. This outcome implies that financial developments significantly reduce the pollution level with respect to APEC economies and suggest that these countries allocate their financial resources to the protection of environmental quality and support their organizations and production units which utilize the eco-friendly technologies (Zaidi et al. 2019). This scenario also concludes that financial development

**Table 3** Second generation panel unit root outcomes

Series	CADF test		CIPS test		Breitung and Das test	
	Level	First $\Delta$	Level	First $\Delta$	Level	First $\Delta$
Intercept						
lnEFP	- 1.699	- 3.261*	- 2.078	- 5.127*	0.192	- 4.795*
lnTECH	- 2.041	- 3.705*	- 2.199**	- 4.687*	1.967	- 3.134*
lnFD	- 2.529*	- 3.671*	- 3.156*	- 5.370*	0.554	- 4.472*
lnGDP	- 1.298	- 2.783*	- 2.016	- 3.259*	1.788	- 2.158**
lnREC	- 1.110	- 3.923**	- 1.466	- 5.073*	0.883	- 2.651*
lnPOP	- 1.722	- 2.161**	- 1.287	- 1.821**	1.604	- 2.001**
Intercept and trend						
lnEFP	- 2.320	- 3.244*	- 2.694**	- 5.189*	- 0.051	- 5.461*
lnTECH	- 2.435	- 3.668*	- 2.544	- 4.681*	- 0.366	- 4.610*
lnFD	- 2.745**	- 3.750*	- 3.222*	- 5.713*	- 1.461***	- 5.792*
lnGDP	- 2.277	- 3.000*	- 2.082	- 3.559*	- 0.480	- 2.891*
lnREC	- 2.451	- 3.926*	- 2.501	- 5.179*	0.960	- 3.033*
lnPOP	- 2.229	- 3.291*	- 1.705	- 1.826	0.950	- 2.331**

\*, \*\*, and \*\*\* indicate 1%, 5%, and 10% level of significance and  $\Delta$  shows difference

**Table 4** Results of Westerlund (According to Westerlund (2007), null hypothesis of no cointegration among series selects a maximum lag length of this technique according to  $4(T/100)^{2/9} \approx 3$  Bartlett kernel width) cointegration test

Statistics	Values	Z-values	P values	Robust P values
$G_\tau$	-3.605*	-4.024	0.000	0.000
$G_a$	-5.777	4.463	0.999	0.968
$P_\tau$	-10.685***	-1.104	0.135	0.088
$P_a$	-5.260	2.907	0.998	0.878

\* and \*\*\* indicate 1% and 10% level of significance

encourages the employment opportunity due to augmentation in investment level that increases the conventional energy demands for the progression of economic development in expense of environmental quality (Shahbaz and Lean 2012). Our empirical findings are consistent in line with (Tamazian et al. 2009; Jalil and Feridun 2011; Charfeddine 2017; Hafeez et al. 2019; Ehigiamusoe et al. 2019; Khalid et al. 2020; Yang et al. 2020b) that financial development significantly improves the environmental quality in different countries. Financial development is also helpful for achieving the targets as set by sustainable development goals (SDGs) vision for 2030. For instance, household credits have the ability to increase the possibilities of environment-friendly projects from companies as well they allow purchasing durable commodities that are eco-friendly by managing the increase in sustainable energy resources (Usman et al. 2020c; Hafeez et al. 2019).

Additionally, renewable energy utilization will lead to cause a reduction in ecological footprint. Particularly, renewable energy utilization has a statistically significant and adverse impact on ecological footprint. If renewable energy use enhances by 1%, environmental degradation will cause to reduce by 0.4274% in the APEC region. This empirical outcome is promoting for the aims of reduction in ecological damages in analyzed economies with policy inference for other economies. These outcomes specify that the utilization of traditional (conventional) energy resources is the key source of environmental degradation. This phenomenon suggests that

there is dire need to swing the economy from non-renewable to renewable energy resource (Ehigiamusoe 2020a, b; Khalid et al. 2020; Usman et al. 2020b). Additionally, public-private policies should encourage the sources of renewable energy utilization and generation to overcome the greenhouse gas pressure on the environment which shows the major involvement in the air pollution (Sinha et al. 2020). Our empirical findings are also in line with some previous studies (Destek et al. 2018; Sharif et al. 2020; Usman et al. 2020a, b).

Moreover, results revealed that economic growth has a positive and significant relationship with the ecological footprint. Accordingly, a 1% increase in affluence in APEC countries will lead to driving in an ecological footprint about 0.5175%. These empirical findings show that encouragement of the level of affluence generally requires more energy demand. Thus, it is a gigantic possibility that APEC countries have developed the major sector of the economy, for instance, industrial, transport, and agriculture. Further, economic growth encourages the economic actions through consumption, purchase, and investment level in which turn to increase the ecological footprint. As the economy move from the low-income to the middle-income phase of development, ecological issues may augment since economic development takes place at the cost of environmental quality (Ehigiamusoe et al. 2020; Usman et al. 2020c; Khalid et al. 2020). Finally, empirical results examine that the long-run effect of population size on environmental pollution has positive and significant as expected. A 1% rise in population size enhances the ecological footprint about 0.458% when other factors remaining the constant. It is well-known phenomenon that population growth is declared as influencing indicator to accelerate environmental deficit (Dunlap and Catton 1979). In this regards, Ehigiamusoe and Lean (2019) who posited that economic growth augments carbon emission in the panel of middle-income countries due to investment in research and development (R&D) in advanced and cleaner technological processes is much lower in developing countries. Our empirical results also coincide with published literature like Hanif and Gago-de-Santos (2017), Ahmed and Long (2012), Wang et al. (2018), Yang et al. (2020a), and Wang and Zhang (2020).

**Table 5** Results of long-run elasticity estimates

Series	FGLS		AMG		CCEMG	
	Coefficient	P value	Coefficient	P value	Coefficient	P value
lnTECH	0.0992**	0.0421	0.3491*	0.0010	0.7801**	0.0390
lnFD	-0.0927*	0.0000	-0.1045**	0.0430	-0.1976	0.4570
lnGDP	0.5175*	0.0000	0.4592	0.7860	0.5598*	0.0000
lnREC	-0.4274*	0.0000	-0.5591**	0.0270	-0.6318***	0.0610
lnPOP	0.4582*	0.0000	0.1945*	0.0000	0.0017	0.9180

\*, \*\*, and \*\*\* signify 1%, 5%, and 10% level of significance

According to Franklin and Ruth (2012), several socio-economic factors with population growth exerts huge pressure on natural resources, consequently, deteriorate the environmental quality. Finally, a 1% augmentation in population size will cause to enhance the ecological footprint level by 0.4582% in APEC countries. These findings are also consistent with published literature by Li et al. (2017), Churchill et al. (2019), and Wang and Zhang (2020) and in contrast with Ganda (2019) and Koçak and Ulucak (2019).

**Results of panel Dumitrescu and Hurlin causality test**

The FGLS, AMG, and CCEMG estimation approaches infer only estimate the magnitude of long-run association among analyzed variables. In order to suggest some valuable policy recommendation, it is essential to know the flow of these causal relationships (either positive or negative). In the presence of CSD and heterogeneity across cross-sections, we applied the Dumitrescu and Hurlin (2012) non-causality approach that allows both of these issues. Moreover, two test statistics (i.e., W-bar and Z-bar) are applied to analyze the significance of the causal relationship. W-bar statistics utilized mean test statistics while Z-bar test statics is applied to analyze the standard normal distribution. The important assumption of this test is that variable should follow the stationary property; in pursuit to this, we transform all variables at integrated of the first order.

The results of pair-wise D-H panel causality test of ecological footprint and its determinants (financial development, technological innovations, economic growth, renewable energy utilization, and population) are applied to analyze the causal association among regression parameters. Figure 1 illustrates the relationship movement of EFP and its determinants, as reported in Table 6. Table 6 explores the panel D-H causality test results which explore the bidirectional causality linkage between EFP and FD, between GDP and EFP, between POP and EFP, between REC and EFP, between TECH and FD, between GDP and FD, between GDP and TECH, between POP and TECH, between POP and GDP, and between REC and POP in case of APEC countries. This implies that an augmentation in financial development and real income have driven the under-developed economies across the APEC region to follow technological innovations activities. However, less use of renewable energy sources has disrupted the world environmental quality through enhanced ecological footprint. Furthermore, the outcomes of this study discovered the unidirectional causality association from TECH to EFP, from POP to FD, from REC to FD, from GDP to TECH, from TECH to REC, and from GDP to REC (see Table 6 and Fig. 1). A unidirectional causality relationship from technological innovation to ecological footprint infers that technological innovation is one of the major determinants of ecological footprint in APEC countries. These D-H

**Table 6** Results of pairwise Dumitrescu Hurlin Panel Causality Tests

Null hypothesis	W-Stat.	Zbar-Stat.	Prob.	Inference
lnFD ⇔ lnEFP	6.39848*	6.81838	0.0000	FD ↔ EFP
lnEFP ⇔ lnFD	4.80778*	4.22857	0.0000	
lnTECH ⇔ lnEFP	4.78317*	3.58426	0.0000	TECH → EFP
lnEFP ⇔ lnTECH	2.36941	0.53411	0.6826	
lnGDP ⇔ lnEFP	4.98682*	4.52006	0.0000	GDP ↔ EFP
lnEFP ⇔ lnGDP	3.80035*	2.58838	0.0096	
lnPOP ⇔ lnEFP	5.89577*	5.99993	0.0000	POP ↔ EFP
lnEFP ⇔ lnPOP	8.17854*	9.71648	0.0000	
lnREC ⇔ lnEFP	3.66776**	2.37252	0.0177	REC ↔ EFP
lnEFP ⇔ lnREC	4.97147*	4.49507	0.0000	
lnTECH ⇔ lnFD	4.46514*	3.67072	0.0002	TECH ↔ FD
lnFD ⇔ lnTECH	3.51602**	2.12547	0.0335	
lnGDP ⇔ lnFD	5.44391*	5.26424	0.0000	GDP ↔ FD
lnFD ⇔ lnGDP	4.67343*	4.00984	0.0000	
lnPOP ⇔ lnFD	6.46584*	6.92805	0.0000	POP → FD
lnFD ⇔ lnPOP	2.63478	0.69073	0.4897	
lnREC ⇔ lnFD	4.00532*	2.92210	0.0035	REC → FD
lnFD ⇔ lnREC	2.78349	0.93284	0.3509	
lnGDP ⇔ lnTECH	6.37261*	7.82115	0.0000	GDP → TECH
lnTECH ⇔ lnGDP	2.34186	0.91744	0.7631	
lnPOP ⇔ lnTECH	6.07268*	6.28795	0.0000	POP ↔ TECH
lnTECH ⇔ lnPOP	7.78554*	9.07663	0.0000	
lnREC ⇔ lnTECH	1.90096	-0.50400	0.6143	TECH → REC
lnTECH ⇔ lnREC	3.51841**	2.12936	0.0332	
lnPOP ⇔ lnGDP	6.86270*	7.57416	0.0000	POP ↔ GDP
lnGDP ⇔ lnPOP	16.4765*	23.2263	0.0000	
lnREC ⇔ lnGDP	2.00574	-0.33340	0.7388	GDP → REC
lnGDP ⇔ lnREC	4.49726*	3.72301	0.0002	
lnREC ⇔ lnPOP	5.25647*	4.95907	0.0000	REC ↔ POP
lnPOP ⇔ lnREC	5.86590*	5.95129	0.0000	

\*, and \*\* denote 1%, and 5% significance level. The symbol ⇔ shows does not Granger cause, while ↔ symbolizes as bidirectional causality and symbol → shows the unidirectional causal relationship

causality relationships among series are coincide with several published studies like Bello et al. (2018), Destek and Sarkodie (2019), Chen et al. (2019), Usman et al. (2020c) and Wang and Dong (2019). In addition, D-H causality test analyzed that the absence of causality relationship between TECH and EFP.

**Conclusion and policy implication**

Primarily the aim of this study is to analyze the effect of technological innovations, financial development, renewable energy utilization, economic growth, and population on the ecological footprint in APEC countries by utilizing balanced longitudinal data for the time period from 1990 to 2017. The current study applies an updated and modern methodology to check the association among series. We applied four CSD tests to confirm the cross-sectional dependency among series. The unit root property of the variable is investigated by

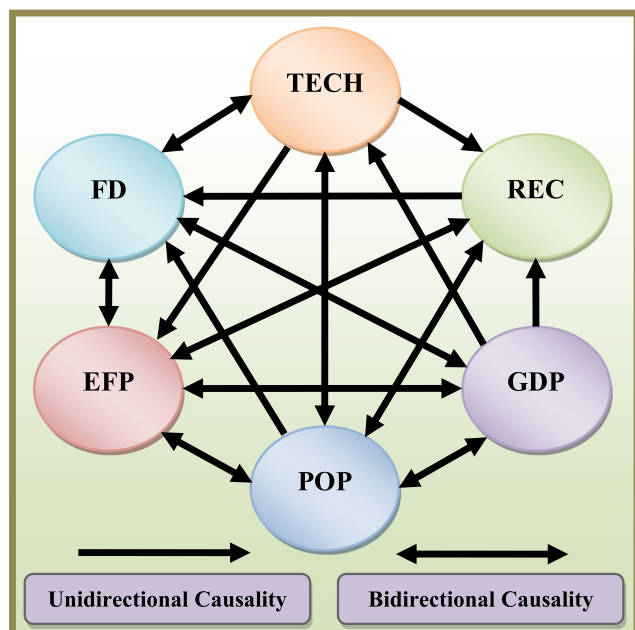


Fig. 1 Causality relationship schema

applied CIPS, CADF, and Breitung and Das, unit root test after confirmation of CSD across variables. To test the long-run cointegration among variables, a panel error correction technique named Westerlund (2007) is examined, and results confirm the presence of long-run association among the under-examined variables.

The results of long-run elasticity are estimated by employing FGLS, AMG, and CCEMG approaches. These approaches have preferred in a sense; this technique is helpful in the presence of cross-sectional dependency, heteroscedasticity, and serial correlation. The results estimated through FGLS show that all explanatory variables (financial development, technological innovations, renewable energy, economic growth, and population size) statistically influence the EFP in APEC countries. Particularly, a 1% influence in financial development and renewable energy utilization will lead to reducing the EFP by 0.0927% and 0.4274%, respectively, while a 1% enhancement in technological innovations, economic growth, and size of the population will raise the ecological footprint by 0.0992%, 0.5175%, and 0.4582%, respectively. Furthermore, panel D-H causality results explored that bidirectional causality linkages exist between EFP and FD, between GDP and EFP, between POP and EFP, between REC and EFP, between TECH and FD, between GDP and FD, between POP and TECH, between POP and GDP, and between REC and POP. In contrast, unidirectional causality association is analyzed to flow from TECH to EFP, from POP to FD, from GDP to TECH, from REC to FD, from TECH to REC, and from GDP to REC in the case of APEC countries.

In order to overcome the pressure on the environment, the current study suggests some valuable policy implications for APEC economies. Initially, results reveal that technological

innovation is one of the crucial influencing factors of environmental quality in APEC countries. Consistent with these outcomes, policymakers and central authority should create more opportunities regarding employment prospects via research and development exercises. When development perspective gradually places, the government of these countries should make consortia to exchange their views and ideas to enhance the share of clean energy sources along with encouraging the energy-efficiency aspects along with technological innovations. In this regard, the people will be capable of creating sustainable employment level that progress in living standards. The results of this improvement in living standards will not only curb the social imbalances but also this will curtail income inequality. With these economic settlements, the government of these countries should identify the need to misaligned state of technical innovations, cleaner technology, and environmental regulations that significantly mitigate the ecological footprint level. In this regard, if such conditions persist, the rising pollution source from industrialization will create intimidation for global sustainability. Hence, there is a dire requirement for building a collective platform (make consortia) in order to extend deepen planning and coordination, R&D collaboration, reinforce combined efforts for cleaner innovation, encourage country-level exchanges, enable to share of eco-friendly technology, and start engineering, scientific, and enterprise alert ventures. The “pollute first” and then “treat” attitude should exchange with a “win, win” approach and the style of economic growth with technological innovations at the cost of environmental quality should be changed in order to protect environmental quality.

Secondly, financial development is also playing a very important role in climate change. In this regard, the long-term projects from these APEC countries should be based on energy-efficient technology and clean and modern energy sources that required more financing. More financial funds should be released for a research and development project into sustainable production and energy efficiency that are technology concentrated. Moreover, developed and sound financial structures, strong financial markets and institutions are more useful in the development of these projects, which turn to condense the conventional sources of energy and greenhouses gases. Hence, the demand for energy consumption can be sustained and restricted via clean financing. Additionally, financial development by private, financial and banking sectors hurts energy utilization, respectively. Therefore, it is necessary to introduce energy-efficient projects through a zero interest rate in the APEC region. Moreover, the policymakers of these countries should propose the finest fiscal incentives to promote renewable energy utilization against conventional energy sources. Additionally, the government should provide innovation subsidies to install eco-friendly projects. Undoubtedly, this will increase the clean and modern energy as compared to non-renewable energy sources. Finally, the

government of these countries should contribute to making sure resources of clean energy use can contend with conventional energy sources like fossil fuels (Bilgili et al. 2017). Lastly, there is a requirement to manage the population by developing a demographic policy that will control population growth not to overtake the environment's carrying potential.

The current study recommends future research that investigates the environmental Kuznets curve (EKC) hypothesis and variance decomposition analysis (VDA) that is useful to investigate the future contribution of analyzed variables towards ecological footprint with a larger time dimension. In addition, future research should consider the variables that represent their cultural activities, which have diverse priorities in every country, such as social and political hurdles and variables related to institutional quality that may influence the technological innovation activities, financial-led growth hypothesis, and its effect on environmental quality.

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**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Compliance with ethical standards

**Competing interests** The authors declare that they have no competing interests.

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