



The influences of renewable electricity generation, technological innovation, financial development, and economic growth on ecological footprints in ASEAN-5 countries

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Received: 22 February 2021 / Accepted: 3 May 2021 / Published online: 11 May 2021
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Abstract

The Southeast Asian countries have experienced significant degrees of economic growth over the years but have not managed to safeguard their environmental attributes in tandem. As a result, the aggravation of the environmental indicators across this region casts a shadow of doubt on the sustainability of the economic growth achievements of the Southeast Asian countries. Against this milieu, this study specifically explores the influence of renewable electricity generation capacity, technological innovation, financial development, and economic growth on the ecological footprints in five Southeast Asian countries namely Indonesia, Malaysia, the Philippines, Thailand, and Vietnam during the period 1985–2016. One of the major novelties of this study is in terms of its approach to assess the renewable energy use-ecological footprint nexus using the renewable electricity generation capacity as an indicator of renewable energy use in the selected Southeast Asian nations. The econometric analysis involves methods that are robust to handling cross-sectional dependency and slope heterogeneity issues in the data. Accordingly, the recently developed Cross-sectional Augmented Autoregressive Distributed Lag estimator is used to predict the short- and long-run impacts on ecological footprints. The major findings suggest that higher renewable electricity generation capacity and technological innovation reduce ecological footprints, while higher financial development and economic growth increase the ecological footprints. Therefore, these findings imply that in forthcoming years, the selected Southeast Asian countries will need to tackle the environmental adversities by enhancing their renewable electricity generation capacities, increasing investment in technological development, greening the financial sector, and adopting environmentally-friendly growth policies. Hence, the implementation of relevant policies, in this regard, can be expected to ensure complementarity between economic growth and environmental welfare across Southeast Asia.

Keywords Renewable electricity · Renewable energy transition · Ecological footprints · Technological innovations · Financial development · ASEAN · CS-ARDL

Introduction

Since the establishment of the Association of the Southeast Asian Nations (ASEAN) in 1967, the Southeast Asian nations

have experienced significant degrees of growth in their respective economies. The ASEAN region as a whole has grown at an average rate of 5.2% over the last couple of years; hence, it has been recognized as one of the fastest-growing

Responsible Editor: Eyup Dogan

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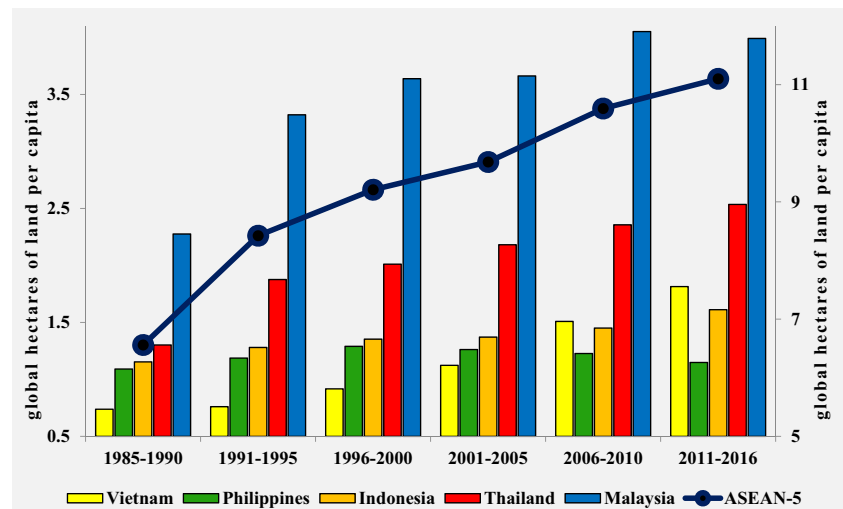
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Fig. 1 Trends in the ecological footprint figures of the ASEAN-5 countries. The total ecological footprints of the ASEAN-5 countries are shown along the secondary axis. Source: Global Footprint Network (GFN 2019)



economic blocs across the globe (Focus Economics 2018; Nasir et al. 2019). However, although the ASEAN countries prospered economically, a perpetual trade-off between higher growth and lower environmental quality has taken place; mostly accredited to the economic growth anchored by natural and fossil sources consumption (Rosenzweig et al. 2010; Kongbuamai et al. 2020; Gormus and Aydin 2020). Between 2011 and 2016, the total volume of carbon dioxide (CO₂) emitted by the ASEAN countries has increased by more than 15% (World Bank 2020). Consequently, the ASEAN region became the third-largest emitter of Greenhouse Gases (GHG) in the world (Ahmed and Le 2020). It is assumed that environmental degradation not only generates adverse effects on economic growth but also deteriorates human health and several other macroeconomic indicators (Yilanci and Pata 2020). Therefore, the aggravation of the environmental quality casts a shadow of doubt on the sustainability of the remarkable growth performances of the ASEAN countries. Therefore, it is critically important to identify the major factors responsible for the deterioration of environmental quality across this region.

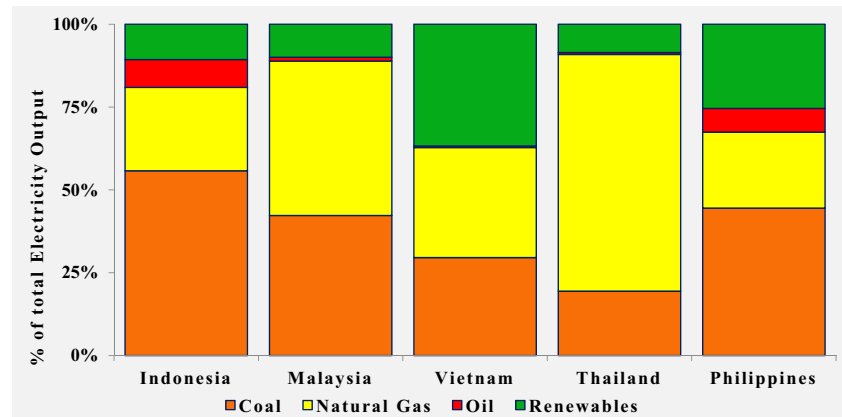
Among the major ASEAN states, this current study focuses on five selected Southeast Asian nations namely Indonesia, Malaysia, the Philippines, Thailand, and Vietnam (ASEAN-5). Accommodating a total population of more than 660 million, the ASEAN-5 countries aim to ensure economic cooperation and economic development within the Southeast Asian region, accounting for almost 3% of the world output level (World Bank 2020). The majority of the economies of the ASEAN-5 countries, over the last decade, have grown at an average rate of more than 5% per year (World Bank 2020). However, alongside such noteworthy economic growth achievements, the environmental quality in most of these nations has worsened. As shown in Fig. 1, it is evident that apart from the Philippines, the environmental attributes in the other four ASEAN nations have persistently deteriorated. Between

the 1985–1990 and 2011–2016 periods, the per capita Ecological Footprints (EF)¹ of Vietnam, Thailand, Malaysia, and Indonesia have registered 2.46, 1.95, 1.75, and 1.40 times, respectively, while the cumulative per capita EF of the ASEAN-5 nations have increased by more than 1.7 times. On the other hand, the per capita EF figures of the Philippines have not increased to a large extent. Besides, the dismal state of the environment in these countries is further highlighted by the fact that all the ASEAN-5 nations are categorized as ecologically. This implies that the EF figures of these nations are greater than their corresponding biocapacities to meet the respective human ecological demand (GFN 2019).

Among the several factors responsible for the aggravation of the environmental well-being in the ASEAN-5 nations, the monotonic fossil fuel dependency of these countries is said to be the most crucial one. Figure 2 portrays the historical trends in the choices of primary energy inputs used for electricity generation in the selected Southeast Asian countries. It can be seen that the ASEAN-5 countries generate a nominal amount of their respective electricity outputs from renewables. In 2015, the renewable electricity output shares of Thailand, Malaysia, Indonesia, Philippines, and Vietnam were 8.54%, 9.96%, 10.65%, 25.41%, and 36.7%, respectively. Hence, these figures highlight that the renewable electricity generation capacities of these countries are significantly low. Thus, phasing out this traditional dependency on fossil fuels for electricity generation purposes can be hypothesized to reduce the rate of extraction and use of these environmentally

¹ The EF measures environmental quality in terms of the amount of bio-productive land required to accommodate the human ecological demands. A rise in the EF figures is interpreted as an aggravation of the environmental quality, and vice-versa. For an in-depth understanding of the methodology of estimating EF, see Rees and Wackernagel (2008), GFN (2019), and Nathaniel and Khan (2020).

Fig. 2 The choices of energy resources for electricity generation in ASEAN-5. Source: World Development Indicators (World Bank 2020)



unfriendly energy resources which, in turn, is likely to improve the ecological statuses of these countries.

The aggravating trends in the EF figures along with the poor renewable energy utilization scenarios across the ASEAN-5 countries motivate this study. Against this background, this current study aims to identify essential macroeconomic factors that can influence the EF figures of the ASEAN-5 countries. Among the major relevant determinants of EF, this study specifically emphasizes the effects of renewable electricity generation capacity, technological innovation, financial development, and economic growth in the ASEAN-5 context. These macroeconomic variables have been acknowledged in the literature to influence the environmental indicators across the globe (Ahmad et al. 2020a; Ahmad and Khattak 2020; Jiang et al. 2021; Ding et al. 2021). Besides, the importance of this study can be understood in several aspects. First, the recent ratification of the Regional Comprehensive Economic Partnership (RCEP) agreement between the ASEAN and the five Asia-Pacific nations can be expected to boost the economic growth of the ASEAN-5 countries. However, given the historical trends in fossil fuel dependency in these countries, this forecasted growth can also accompany environmental degradation whereby the EF figures of these can be anticipated to further surge in the years to come. Second, since all these five Southeast Asian nations have pledged to contribute to the global attainment of the Sustainable Development Goals (SDG) agenda of the United Nations and have also ratified the Paris Agreement, it is obligatory for these nations to identify the appropriate channels through which they can inhibit the deterioration of their respective environmental attributes. In these regard, the outcomes from this study can be expected to unearth key policy implications which can enable the ASEAN-5 countries to achieve environmental sustainability and, therefore, help them to comply with their international environmental welfare commitments. This study contributes to empirical literature in several aspects.

First, as opposed to the existing studies that have predominantly used CO₂ emissions to measure environmental quality in the ASEAN context (Chandran and Tang 2013; Heidari et al. 2015; Gill et al. 2020), this study focuses on analyzing the EF as

an alternative environmental indicator. Not many previous studies modeled the macroeconomic determinant of EF in cases of the ASEAN-5 countries. Besides, it is believed that compared to CO₂ emissions, the EF are a more comprehensive indicator of environmental well-being (Nathaniel and Khan 2020). The EF captures the environmental consequences of goods and services, encompassing six categories of bio-productive land use type (grazing land, forest land, cropland, ocean, carbon footprint, and built-up land). This current study is one of the few studies that have used the EF to quantify environmental degradation in the selected ASEAN countries. The justification behind the decision to use the EF is driven by the fact that CO₂ emissions have been acknowledged as a vague measure of environmental degradation since it does not consider the multidimensionality of the environmental hardships (Raza and Shah 2018; Balsalobre-Lorente et al. 2020; Xue et al. 2021; Pata and Caglar 2021). In contrast, the EF is considered to be a comprehensive indicator of environmental quality since it encompasses a wide array of environmental concerns (Rees and Wackernagel 2008).

Second, this current study evaluates the environmental impacts of renewable energy use from the supply-side channel. The previous studies have predominantly explored the renewable energy-environmental quality nexus for the ASEAN countries using the renewable energy consumption figures (Liu et al. 2017; Destek et al. 2018; Nathaniel and Khan 2020; Anwar et al. 2021). However, addressing the supply-side channel in this regard is also essential for appropriate policy-making purposes. Therefore, this study uses the renewable electricity generation capacities of the selected ASEAN-5 countries to scrutinize the impacts of renewable energy on the environment. Besides, since the total volume of renewable energy consumed within a country is said to be conditional on its maximum capacity to generate renewable electricity, the renewable electricity generation capacity can be considered as a more relevant proxy for estimating the environmental impacts associated with renewable energy use. To the best of the authors' knowledge, this is the first study that uses the renewable electricity generation capacity to model the EF levels for the ASEAN-5 countries.

Third, this study is also one of the ones which link technological innovations and the EF levels in the context of the selected ASEAN countries. A limited number of the preceding studies have assessed the technological innovation-environmental quality nexus using panel data sets that included some of the ASEAN nations as well (Usman and Hammar 2020). In the era of the Fourth Industrial Revolution, technical innovation is expected to exert a crucial role in both contributing to economic growth and simultaneously reducing environmental degradation (Alvarez-Herranz et al. 2017; Raheem et al. 2020; Balsalobre-Lorente et al. 2020; Li et al. 2021). Although not many existing studies have isolated the effects of technological innovations on the quality of the environment in the selected ASEAN nations, the few which did have rather used the energy efficiency levels as a proxy for technology. In contrast, this study uses the number of patent applications to proxy technological innovations since the patents are referred to as more precise technological innovation indicators.

Lastly, this study contributes to the related environmental economics literature in the ASEAN context by predicting the short- and long-run elasticities of EF using the recently introduced Cross-sectional Augmented Autoregressive Distributed Lag (CS-ARDL) estimators of Chudik et al. (2013). Although the existing studies have used other panel data estimators to estimate the elasticities of EF, the CS-ARDL method is yet to be applied in the context of the selected ASEAN nations. More importantly, the CS-ARDL method has several advantages over the conventionally-used techniques, making it a relatively more appropriate elasticity estimator.

The structure of the rest of this paper is as follows. Section 2 presents the literature review. The empirical model, data attributes, and the econometric methodology are explained in section 3. The empirical results are reported and discussed in section 4. Finally, section 5 concludes by suggesting some relevant policy measures which the selected ASEAN countries can adopt to ensure environmental sustainability.

Literature review

This section is segmented into two smaller sub-sections: the former presents the theoretical frameworks which explain the potential channels through which different macroeconomic variables influence the environmental quality while the latter summarizes the corresponding empirical studies documented in the literature.

Theoretical framework

Achieving environmental sustainability has established itself as one of the major global agendas. Besides, the SDG declarations of the United Nations have also emphasized the

importance of ensuring environmental sustainability alongside socioeconomic sustainability across the globe. In particular, several of the 17 SDG (Goals 11, 13, 14, and 15) are specifically aimed at the implementation of policies that can safeguard the environmental attributes. Although several environmental modeling approaches portray the mechanisms through which different macroeconomic variables affect the well-being of the environment, this study builds upon the theoretical underpinnings of the Stochastic Impacts by Regression on Population, Affluence, Technology (STIRPAT) model of Dietz and Rosa (1994). This model is a variant of the IPAT model of Ehrlich and Holdren (1971) which portrays that environmental impact (I) within an economy is determined by the size of the population (P), Affluence (A), and the level of Technology (T). However, a major limitation of this model was that it questionable assumes the environmental impacts of the explanatory variables to be in fixed proportions (Usman and Hammar, 2020, b). To address the limitation of the IPAT model, Dietz and Rosa (1994) introduced a stochastic version of the IPAT model by relaxing the inappropriate assumption of fixed effects of population, affluence, and technology on environmental quality. Subsequently, several studies have modeled environmental quality by augmenting key macroeconomic variables into the STIRPAT model.

As far as the environmental impacts of affluence are concerned, it is believed that as the national output level within an economy increases, synonymous with economic growth, it is likely to increase the demand for natural and financial resources. Under such a circumstance, relatively less affluent economies tend to utilize environmentally unfriendly resources to generate output which, in turn, results in a deterioration in environmental quality (Brizga et al. 2013). On the other hand, it is also believed that affluent economies are able to invest in technological development which can be effective in mitigating environmental degradation along with the growth of the economy (Khattak et al. 2020). In line with these contrasting impacts, researchers have often claimed the economic growth-environmental quality nexus to be non-linear. This phenomenon is popularly highlighted in the Environmental Kuznets Curve (EKC) hypothesis of Grossman and Krueger (1991) which postulates that economic growth initially reduces environmental quality but improves it provided a certain level of growth is achieved (Ahmad et al. 2021; Khan et al. 2021; Li et al. 2021). Therefore, promoting green growth policies is extremely important since such policies not only facilitate the overall well-being of the environment but also helps to protect ecological resources (Ikram et al., 2020; Abid et al., 2021).

On the other hand, technological innovation is believed to influence the quality of the environment. Developing countries with low levels of technology are often obligated to make use of environmentally unfriendly energy resources whereby a

trade-off between higher economic growth and lower environmental quality can be expected. In contrast, technological innovation is believed to mitigate the adverse environmental impacts of economic growth by making use of relatively more environmentally-friendly energy resources (Ozcan and Ulucak 2020). Similarly, it has been argued in the literature that technological innovation can help to develop technologies which can monitor, control, and restrict the use of environmentally unfriendly resources, in particular (Murshed et al. 2021a). Besides, technological innovation is also hypothesized to exhibit favorable impacts in the respect of achieving the Paris Agreement objectives by reducing the energy consumption-induced GHG emissions (IAEA 2018). In the same vein, several studies have also recommended investment in technological development to facilitate the use of relatively cleaner energy resources which can be an effective means of reducing the negative environmental impacts (Chen et al. 2017). It has been asserted that consumption of fossil fuel-based electricity deteriorates the environment due to fossil fuels containing hydrocarbons (Bento and Moutinho, 2016; Murshed 2020). Consequently, the combustion of fossil fuels for producing electricity results in emissions of harmful gases into the atmosphere, thus degrading the atmospheric quality (Murshed et al. 2021b; Murshed 2021a). Conversely, generating electricity for renewable resources, which do not contain hydrocarbons, is said to improve the quality of the environment by reducing the extraction of fossil fuels and curbing the overall GHG emission levels (Farhani and Shahbaz 2014; Belaïd and Zrelli, 2019). The idea of transitioning from non-renewable to renewable energy has also been highlighted in Goal 7 under the SDG declarations of the United Nations (Murshed 2021b). More importantly, one of the several targets of Goal 7 is to substantially increase the share of renewables in the global energy mix. This is particularly relevant in the context of this study since it attempts to ascertain the impacts of enhancing renewable electricity generation capacity on environmental quality in the ASEAN-5 countries.

Several studies have also documented evidence of equivocal environmental impacts of financial development across the globe (Umar et al. 2020; Li et al. 2021; Xue et al., 2021). For instance, financial development is acknowledged to facilitate capital investments to generate output which, in turn, can be hypothesized to deteriorate the environment, especially in the context of fossil fuel-dependent countries (Abokyi et al. 2019). On the other hand, financial development can also be expected to facilitate investment in green technologies whereby the adverse environmental impacts can be minimized to a large extent (Charfeddine et al. 2018). Financial development can also ensure access to low-interest loans for research and development which can be effective in improving the overall quality of the environment (Hayat et al. 2018).

Lastly, many existing studies have also shed light on the environmental impacts of population growth. In the majority

of these studies, it has been argued that a rise in the population exerts pressure on the human demand for ecological reserves which stimulates environmental deterioration (Edenhofer and Kalkuhl, 2011; Mohsin et al., 2019). However, recent studies have also highlighted that human capital development can reduce the adverse environmental impacts associated with population growth (Danish et al. 2019; Ahmed et al. 2020).

Empirical evidence

Environmental quality is believed to be influenced by a wide array of macroeconomic variables, including economic growth, energy use, technological innovations, and financial development. Hence, this sub-section chronologically summarizes the relevant empirical evidence that has been documented in the literature.

The literature on the nexus between economic growth and environmental quality

As far as the environmental impacts of economic growth are concerned, the preceding studies have conventionally explored the economic growth-EF nexus under the theoretical framework of the EKC hypothesis. However, the existing studies in this regard have reported mixed findings. Among these, the EKC hypothesis for EF was validated by Kongbuamai et al. (2020) for eight ASEAN states, Hassan et al. (2019) for Pakistan, Narayan and Narayan (2010) for 43 developing countries, and Balsalobre-Lorente et al. (2019a, b) for MINT (Mexico, Indonesia, Nigeria, and Turkey) countries. Conversely, the EKC hypothesis for EF was invalidated in the studies by Aydin et al. (2019) for 26 European Union (EU) members, Yilanci and Pata (2020) for China, and Aydin and Turan (2020) for BRICS (Brazil, Russia, India, China, and South Africa) countries. Ansari et al. (2020) employed the GMM econometric methodology to confirm a direct link between economic growth and the EF for 37 Asian countries between 1991 and 2017. Ahmed et al. (2020) found that economic growth and urbanization processes increase the EF in China. Dogan et al. (2020) concluded that the EKC was not validated for BRICS and Turkey (BRICST), being energy structure and energy intensity the fundamental driving forces of the EF.

The literature on the nexus between energy consumption and environmental quality

The environmental impacts of energy use are said to be determined by the nature of the energy resource consumed. For instance, the predominant reliance on fossil fuels, which is the case of most of the ASEAN states, can impose adverse impacts on the environment (Apergis and Payne, 2014). In contrast, the use of non-fossil renewable energy resources

can be assumed to improve the quality of the environment (Ito, 2017). Danish and Ulucak (2020) concluded that renewable energy promotes environmental quality in BRICS, concluding that this region requires a paradigm shift to clean energy to accomplish the SDG. Nathaniel et al. (2020a) showed that renewable energy contributes to correct the EF in the BRICS from 1990 to 2014, showing the same evidence in MENA countries in Nathaniel et al. (2020b). Although the environmental effects associated with renewable energy are often assessed by the impacts of higher renewable energy use on the environmental indicators, it is equally important to evaluate the impacts of the renewable electricity generation capacities on the environment. Besides, investigating the nexus between renewable electricity generation capacity and environmental quality is also critically important from the perspective of reducing the production-based environmental adversities. It has been acknowledged in the literature that ensuring sustainability in the consumption and production services is pertinent for protecting the environmental attributes (Xue et al., 2021).

Moreover, it is to be noted that the electricity sectors of the selected ASEAN nations are overwhelmingly reliant on primary fossil fuel supplies for electricity generation purposes; most of these five nations produce less than one-fourth of respective total electricity outputs from renewable resources (World Bank, 2020). This is a clear indication of the low renewable electricity generation capacities of these countries. Fossil fuel dependency is said to be a major contributor to environmental degradation for the ASEAN countries. In this regard, a rise in the renewable electricity generation capacity can be hypothesized to exert favorable environmental outcomes. As far as the empirical evidence on the energy consumption-EF nexus is concerned, Usman et al. (2021) concluded that higher renewable energy consumption levels reduced the EF figures of the 15 highest CO₂-emitting countries. Similar results were reported by Alola et al. (2019) for 16 EU countries. On the other hand, Destek and Sinha (2020) found evidence of non-renewable energy consumption increasing the EF and renewable energy consumption reducing the EF in the context of 24 Organization for Economic Cooperation and Development (OECD) countries. Besides, the country-specific results were homogenous to the panel results for most of the OECD nations. In the ASEAN context, Nathaniel and Khan (2020) found higher renewable energy consumption levels to account for lower EF figures in the long run.

The literature on the nexus between technological innovations and environmental quality

Technological innovations are considered to be crucial means of reducing environmental hardships (Álvarez-Herranz et al. 2017; Balsalobre-Lorente et al. 2018; Li et al. 2021). For instance, technological innovations can directly conserve the environmental attributes by developing environmental-related

technologies, which can be interpreted as environmental regulations that inhibit the disposal of wastes into the ecosystem (Nathaniel et al. 2021). On the other hand, technological innovations can also indirectly lead to environmental improvement by increasing energy efficiency levels (Wang and Wang, 2020). Moreover, since technological innovation stimulates renewable energy transition (Bekun et al. 2019), it can also help expand the renewable electricity generation capacities of the ASEAN countries. This, in turn, can be anticipated to enhance environmental well-being further.

Using data of 22 emerging economies, including Malaysia and the Philippines from the Southeast Asian region, Ahmad et al. (2020b) found evidence of technological innovation mitigating the EF both in the short- and long run. Similarly, Nathaniel et al. (2021) recommended enhancing environmental-related technological innovations for effectively reducing the EF of the Next Eleven countries. On the other hand, Usman and Hammar (2020) concluded that technological innovation is detrimental to environmental quality since it boosts the EF of the Asia Pacific Economic Cooperation (APEC) countries. In another relevant study by Sabir and Gorus (2019), the authors found technological innovations to be ineffective in influencing the EF figures of selected South Asian countries. Therefore, based on the findings documented in the literature, it can be said that the environmental impacts associated with technological innovations are uncertain.

The literature on the nexus between financial development and environmental quality

The environmental impacts of financial development can be either positive or negative. For instance, financial development can be a source of finance for investment in the economy, which, in turn, can exert environmental adversities (Khan et al., 2019). On the other hand, financial development can also be linked to the development of the renewable energy sector, whereby a favorable environmental impact can be expected (Liu et al., 2021). Hence, the effects of financial development on the environmental quality in the selected ASEAN nations can be ambiguous. In a recent study by Usman et al. (2021), the authors asserted that financial development reduces EF in the 15 highest CO₂-emitting countries. Similarly, in the context of Nigeria, Omoke et al. (2020) also concluded that financial development is negatively correlated to the EF figures. Conversely, using data from 59 BRI countries, Baloch et al. (2019) found financial development to worsen the environmental quality by increasing the EF. In another relevant study on 110 developed and less-developed nations, Yasin et al. (2020) claimed that financial development reduces the EF only in the less-developed nations. In another recent study on selected South Asian economies, Murshed et al. (2021c) asserted that financial development is

detrimental to the environment across South Asia since it boost both the EF and the CO2 emission levels.

Empirical model, data and econometric methodology

Empirical model construction and data

The empirical model used in this study has been constructed as per the theoretical framework explained earlier. To model the macroeconomic determinants of EF of the selected ASEAN countries, the per capita EF of these nations are expressed as a linear function of economic growth, renewable electricity generation capacity, technological innovation, financial development, and population growth. The underlying model can be specified as:

$$LnEF_{it} = \alpha_0 + \beta_1 lnGDP_{it} + \beta_2 lnREC + \beta_3 lnTI_{it} + \beta_4 lnFD_{it} + \beta_5 lnPG_{it} + \varepsilon_{it} \tag{1}$$

where the subscript *i* represents a cross-section of ASEAN countries (Indonesia, Malaysia, Philippines, Thailand, and Vietnam); *t* indicates the number of years considered in this study (1985–2016); α_0 is the intercept parameter; and β_k ($k = 1, 2, \dots, 5$) are the parameters for the elasticities of EF which are to be predicted. The dependent variable EF_{it} is the natural logarithm of the per capita EF of the ASEAN nations. Higher EF figures can be interpreted as deterioration in the environmental quality, while a lower value is considered as an improvement in environmental quality. In this regard, the positive sign of the elasticity parameters would indicate the adverse environmental impacts of the associated explanatory variable and vice-versa. Among the explanatory variables, GDP, REC, TI, LNFD, and LNPG refer to the gross domestic product (proxy for economic growth), renewable electricity generation capacity (a proxy for renewable energy),

Table 2 Descriptive statistics and correlation analysis

	lnEF	lnGDP	lnTI	lnREC	lnPG	lnFD
Panel A: Descriptive statistics						
Minimum	12.551	3.148	1.793	0.039	2.573	-0.994
Maximum	19.905	6.945	7.360	4.180	5.250	1.091
Mean	18.542	5.141	5.169	1.512	3.941	0.401
St. Dev.	0.758	0.832	1.236	0.860	0.747	0.459
Skewness	0.058	0.008	1.556	3.155	0.022	1.052
Kurtosis	1.518	1.033	2.205	1.516	1.032	2.518
Panel B: Correlation matrix						
lnEF	1.000					
lnGDP	0.732	1.000				
lnTI	0.425	0.651	1.000			
lnREC	0.338	0.110	0.283	1.000		
lnPG	0.415	0.233	0.534	0.460	1.000	
lnFD	-0.398	-0.404	-0.526	-0.559	-0.340	1.000

technological innovation, financial development, and population growth rate, respectively.

Annual frequency data spanning from 1985 to 2016 for the ASEAN-5 countries has been used in the analysis. The period of analysis and the ASEAN countries sample were chosen based on data availability. Most of the variables have been transformed into their natural logarithms for the ease of the elasticity estimations. Table 1 reports the definition and the unit of measurement, and the corresponding data source for all the variables used in this study. Table 2 presents the descriptive statistics and the correlation matrix concerning the variables. It can be seen that all the variables are positively skewed and platykurtic. Besides, the correlation matrix reveals a moderate correlation between the variables.

Econometric methodology

The econometric strategy used in this study is five-fold. First, the cross-sectional dependency and slope heterogeneity tests

Table 1 Description of variables

Variables	Symbol	Measure	Source
Ecological Footprint	lnEF	Global hectares of land per capita	GFN (2019)
Economic growth	lnGDP	Per capita GDP in constant 2010 US\$	World Bank (2020)
Renewable electricity generation capacity	lnREC	Total capacity to produce electricity from renewable resources in millions of kilowatts	USEIA (2020)
Technological Innovation	lnTI	No. of patent applications by resident	World Bank (2020)
Financial Development	lnFD	Domestic credit to the private sector (% of GDP)	World Bank (2020)
Population growth	lnPG	Annual population growth rate (%)	World Bank (2020)

are conducted to detect the possibility of these issues existing in the data. Second, the order of integration among the variables is ascertained by performing the unit root analysis. Third, the long-run relationships between the variables are evaluated using the cointegration analysis. Fourth, the short- and long-run elasticities of EF are estimated by conducting the regression analysis. Lastly, the causality analysis is performed to unearth the causal associations between the variables.

Cross-sectional dependency and slope heterogeneity analyses

The problem of cross-sectional dependency arises when a certain macroeconomic shock exerts similar impacts on the cross-sectional units within a panel data set whereby these cross-sections are considered as cross-sectionally dependent. Cross-sectional dependency leads to the estimation of biased outcomes (Munir et al., 2020). In the ASEAN region, the cross-sectional dependency issues derive from the existence of spillover effects, trade agreements, or international treaties, among others. So, these nations vary in terms of their per capita national income level. In this regard, this study uses the Breusch-Pagan (1980) Lagrange Multiplier (LM) and Pesaran (2004) and the tests of cross-sectional dependence. The test statistics under these methods are predicted under the null hypothesis of cross-sectional independence. Hence, the rejection of the test statistic would affirm the existence of cross-sectional dependency in the data. Let us consider a panel data model which can be specified as:

$$y_{it} = \alpha_i + \beta'x_{it} + \varepsilon_{it} \quad i = 1, 2, \dots, N \quad (2)$$

where the ε_{it} may exhibit cross-sectional dependence.

The hypothesis of interest which assumes cross-sectional independence is shown as:

$$H_0 : E(\varepsilon_{it}\varepsilon_{jt}) = 0; \quad \forall_t \text{ for all } i \neq j \quad (3)$$

against the alternative hypothesis of cross-sectional dependence which can be shown as:

$$H_1 : E(\varepsilon_{it}\varepsilon_{jt}) \neq 0; \quad \forall_t \text{ for some } t \text{ and some } i \neq j \quad (4)$$

where the number of possible pairing $(\varepsilon_{it}, \varepsilon_{jt})$ rises with N.

Under the Breusch and Pagan (1980) approach, a Lagrange multiplier (LM) statistic was proposed for testing the null of zero cross-equation error correlations, which is defined as:

$$LM = T \sum_{i=1}^{N-1} \sum_{j=i+1}^N \hat{\rho}_{ij}^2 \quad (5)$$

where $\hat{\rho}_{ij}$ is the sample estimate of the pair-wise Pearson correlation coefficient of the residuals

$$\hat{\rho}_{ij} = \hat{\rho}_{ji} = \frac{\sum_{t=1}^T e_{it}e_{jt}}{(\sum_{t=1}^T e_{it}^2)^{1/2} (\sum_{t=1}^T e_{jt}^2)^{1/2}} \quad (6)$$

where e_{it} is the Ordinary Least Squares (OLS) estimate of ε_{it} in Eq. (2). LM is asymptotically distributed as chi-squared with $N(N-1)/2$ degrees of freedom under the null hypothesis, as $T \rightarrow \infty$ with N fixed.

Similarly, the Pesaran (2006) cross-sectional dependency test statistic is also estimated under the null hypothesis of cross-sectional independence and can be specified as:

$$CD_{pesaran} = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^N T_{ij} \hat{\rho}_{ij}^2 \rightarrow N(0, 1) \quad (7)$$

Similar to the issue of cross-sectional dependency, the existence of slope heterogeneity also compromises the unbiasedness of the empirical estimates. Slope heterogeneity concerns are likely to occur due to the country-specific dissimilarities among the cross-sectional units, to which the ASEAN nations are no exception. Besides, the renewable electricity generation capacities of these nations are also not homogenous. Thus, it is important to conduct the slope heterogeneity test. This paper uses the Pesaran and Yamagata (2008) test. This test predicts two test statistics ($\tilde{\Delta}$ and $\tilde{\Delta}_{adj.}$) under the null hypothesis of slope homogeneity. Therefore, the rejection of these test statistics would affirm the slope heterogeneity issues in the data.

The results from the cross-sectional dependency and slope heterogeneity analyses are reported in Table 3. The statistical significance of the test statistics confirms the issues of cross-sectional dependency and slope heterogeneity in the data. Following the confirmation of these issues, the appropriate unit root, cointegration, regression, and causality methods are chosen.

The panel unit root analysis

Conducting the unit root analysis is pertinent for ascertaining the order of integration among the variables (Murshed 2021c; Qin et al. 2021; Murshed et al. 2021d). The first-generation panel unit root testing methods assume cross-sectional independence and are not efficient in handling cross-sectionally dependent panel data sets (Murshed et al. 2020a, b; Murshed and Dao 2020). Since the cross-sectional dependency issues have been identified, the application of the first-generation methods is not appropriate. Hence, the second-generation panel unit root methods proposed by Pesaran (2007) are used. Following Wang et al. (2020) and Murshed et al. (2020c), this study applies the Cross-sectionally augmented Dickey-Fuller (CADF) and the Cross-sectionally augmented Im-Pesaran-Shin (CIPS) panel unit root tests. In the testing procedure, the null hypothesis of unit root under cross-sectional dependency is tested against the alternative, which implies the stationary process. Before describing the formulation CIPS test, the CADF test should be described because CIPS test

Table 3 Cross-sectional dependency and slope heterogeneity test results

Panel A: Cross-sectional dependency analysis				
Variable	Breusch-Pagan (1980)		Pesaran (2004)	
	Statistic	Prob.	Statistic	Prob.
lnEF	209.781***	0.000	14.082***	0.000
lnGDP	293.342***	0.000	17.116***	0.000
lnREC	261.631***	0.000	16.161***	0.000
lnTI	186.911***	0.000	13.373***	0.000
lnFD	89.082***	0.000	6.708***	0.000
lnPG	245.541***	0.000	15.617***	0.000

Panel B: Pesaran and Yamagata (2008) slope heterogeneity analysis		
Test statistics	Value	P value
$\tilde{\Delta}$	4.104***	0.000
$\tilde{\Delta}_{adj}$	4.643***	0.000

***indicates significance at 1%

is mainly based on the CADF unit root test. The main regression model of CADF test can be written as follows:

$$\Delta y_{it} = \alpha_i + \rho_i y_{it-1} + \beta_i \bar{y}_{t-1} + \sum_{j=0}^k \gamma_{ij} \Delta \bar{y}_{it-1} + \sum_{j=0}^k \delta_{ij} y_{it-1} + \varepsilon_{it} \tag{8}$$

where α_i , k , and \bar{y}_t are deterministic term, lag order, and the cross-sectional mean of time t , respectively. In the next stage, t -statistics are computed with the *ADF* statistics for each cross-section. Then, averaging CADF statistics for each cross-section gives the *CIPS* statistics as follows;

$$CIPS = \left(\frac{1}{N} \right) \sum_{i=1}^N t_i(N, T) \tag{9}$$

These tests are said to be robust in handling heterogeneous and cross-sectionally dependent data sets (Li et al. 2021). The CADF and CIPS test statistics are predicted under the null hypothesis of non-stationarity. Hence, the rejection of the test statistics would affirm the stationarity of the corresponding series and also determine its order of integration. The unit root analysis is followed by the panel cointegration analysis.

The panel cointegration analysis

The presence of long-run associations between the variables of concern is a prerequisite to estimating the long-run elasticities (Murshed and Alam 2021; Ma et al. 2021; Rehman et al. 2021). Hence, following Sharif et al. (2019), the Westerlund (2007) second-generation panel cointegration analysis is performed in this study. This technique, as opposed to the conventionally used first-generation panel cointegration methods, provides stable and accurate estimates of the cointegrating properties by accounting for the cross-sectional dependency issues in the data (Gözgör and Can 2017). Under

the Westerlund (2007) approach, four test statistics (Gt, Ga, Pt, and Pa) are predicted under the null hypothesis of non-cointegration. Westerlund (2007) considers that $\alpha_i = 0$ for all i in the case of non-cointegration (null hypothesis). There are two alternative hypotheses in this case:

First, $\alpha_i = \alpha < 0$ for all i , which means the panel is cointegrated. The panel test statistic recommended for this hypothesis is depicted as follows:

$$P_T = \frac{\hat{\alpha}}{SE(\hat{\alpha})} \text{ and } P_\alpha = T \hat{\alpha} \tag{10}$$

where $\hat{\alpha}_i$ estimates the homogeneous speed of error correction for all units and the standard error of $\hat{\alpha}$ is $SE(\hat{\alpha}_i)$.

Second, $\alpha_i < 0$ for at least one i , meaning that one or more cross-sectional units are cointegrated. The following group-mean test statistics are considered for testing this hypothesis:

$$G_t = \frac{1}{N} \sum_{i=1}^N \frac{\hat{\alpha}_i}{SE(\hat{\alpha}_i)}; \tag{11}$$

$$G_\alpha = \frac{1}{N} \sum_{i=1}^N \frac{T \hat{\alpha}_i}{\hat{\alpha}_i(1)} \tag{12}$$

where $\hat{\alpha}_i$ is the parameter estimate for unit i and $SE(\hat{\alpha}_i)$ is the associated standard error

$$\hat{\alpha}_i(1) = 1 - \sum_{j=1}^{p_i} \hat{\alpha}_{ij} \tag{13}$$

The Westerlund (2007) test is ideal for solving heterogeneity and cross-sectional dependence with an asymptotically normal distribution and good small-sample properties using bootstrap (Altıntaş and Kassouri, 2020). Therefore, rejection of these test statistics affirms the

presence of cointegrating relationships between the dependent and the independent variables and fulfills the pre-requisite for estimating the long-run elasticities. The cointegration analysis is followed by the panel regression analysis.

Panel regression analysis

In the presence of cross-sectional dependency and slope heterogeneity uses in the data, it is pertinent to choose appropriate regression estimators that can simultaneously account for these problems within the elasticity estimation processes. However, the majority of the conventionally used methods used in the literature have primarily addressed the cross-sectional dependency issues in the data while ignoring the slope heterogeneity concerns. In contrast, this study uses the CS-ARDL method of Chudik et al. (2013) since it tackles both the abovementioned issues in tandem. The CS-ARDL panel regression estimator is a modified version of the Pooled Mean Group (PMG) estimator of Pesaran et al. (1999). It is said that in the context of unobserved common factors existing in the data, the CS-ARDL approach, compared to the PMG method, predicts the elasticities more efficiently (Chudik et al. 2016). Besides, the choice of the CS-ARDL was influenced by its other advantageous features. Firstly, the CS-ARDL estimator predicts both the short- and long-run elasticities, whereas the other relevant methods are mainly used for predicting the long-run elasticities. Secondly, the CS-ARDL method is also robust to handling endogeneity issues that can arise from the possible reverse causalities between the variables included in the model. Thirdly, this method also accommodates the serial-correlation issues in the data and also addresses common-correlation bias issues. Lastly, the CS-ARDL method corrects misspecification bias in the model.

Under the CS-ARDL approach, the problem of cross-sectional dependency is accounted for by augmenting the right-hand side variable set with the cross-sectional averages of the regressors, the dependent variables, and a series of their lag values. These additional terms are meant to address the cross-sectional correlation in the error term. The augmented version of the model is presented as follows:

$$\begin{aligned} \Delta y_{it} = & \mu_i + \alpha_i \left(y_{i,t-1} - \theta' x_{i,t-1} + \alpha_i^{-1} n_i \bar{y}_t + \alpha_i^{-1} y'_{i} \bar{x}_t \right) \\ & + \sum_{j=1}^{p-1} \varnothing_{ij} \Delta y_{i,t-j} + \sum_{j=0}^{q-1} \delta_{ij} \Delta x_{i,t-j} + \sum_{j=0}^{p-1} v_{ik} \Delta \bar{y}_{t-j} \\ & + \sum_{j=0}^{q-1} v_{ik} \Delta x_{t-j} + \varepsilon_{it} \end{aligned} \tag{14}$$

where y_t and x_t represent the cross-section average of y_{it} and x_{it} . In Eq. (14), the short-term and long-term behavior of the cross-sectional correlation is distinguished. Furthermore, only the level parts of cross-sectional averages are included in the

long-term equilibrium relationship in parentheses which is consistent with the suggestion of (Eberhardt and Presbitero 2015). The long-run coefficients associated with y_{it} and x_{it} , that is θ_i , and the rate of adjustment back to equilibrium, α_i , are the main coefficients of interest. In order to ensure completeness, the short-run coefficients, $\varnothing_{i,j}$ and δ_{ij} are also reported.

For a robustness check of the elasticity estimates across alternative regression techniques, the Augmented Mean Group (AMG) and the Common-Correlated Effects Mean Group (CCEMG) estimators of Pesaran (2006) and Bond and Eberhardt (2013), respectively, are also used in this study. However, these methods can only predict the long-run elasticities, whereby the robustness of the findings is checked only for the long run. Finally, the regression analysis is followed by the causality analysis. The AMG estimator proposed by Eberhardt and Teal (2010) also addresses the cross-sectional dependency and slope heterogeneity concerns and involves a two-step procedure:

$$\begin{aligned} \text{AMG-stage 1 :} \quad \Delta y_{it} = & \alpha_i + b_i \Delta x_{it} + c_i f_t \\ & + \sum_{t=2}^T d_t \Delta D_t + \varepsilon_{it} \end{aligned} \tag{15}$$

$$\text{AMG-stage 2 :} \quad \hat{b}_{AMG} = N^{-1} \sum_{i=1}^N \hat{b}_i \tag{16}$$

where f_t is the unobserved common factor, while y_{it} and x_{it} are the observables. b_i is the country-specific estimates of coefficients, d_t the time dummies, and \hat{b}_{AMG} is the AMG estimator.

CCEMG estimator developed by Pesaran (2006) considers the cross-sectional dependence. Before obtaining the coefficients, first, Eq. 17 is combined as follows:

$$y_{it} = \delta_0 + \delta_1 x_{it} + \varepsilon_{it} \tag{17}$$

where y_{it} is unemployment, $x_{i,t}$ is the vector of independent variables and the residual term (ε_{it}) is a multifactor residual term. The multifactor residual terms are constructed as follows:

$$\varepsilon_{it} = \lambda'_i UF_t + u_{it} \tag{18}$$

where UF_t is the $m \times 1$ vector of unobserved common factors. Besides, Pesaran (2006) utilizes cross-sectional averages, $\bar{y}_t = \frac{1}{N} \sum_{i=1}^N y_{it}$ and $\bar{x}_t = \frac{1}{N} \sum_{i=1}^N x_{it}$ to deal with cross-sectional dependence of residuals as observable proxies for common factors. In the next step, slope coefficients and their cross-sectional averages are consistently regressed as follows:

$$y_{it} = \delta_0 + \delta_1 x_{it} + \alpha \bar{y}_t + c \bar{x}_t + \varepsilon_{it} \tag{19}$$

Pesaran (2006) refers to the computed OLS estimator $\hat{B}_{i,CCE}$ of the individual slope coefficients $B_i = (\delta_1, \dots, \delta_n)$ as the Common Factor Correlated Effect (CCE) estimator:

$$\widehat{B}_{i,CCE} = \left(Z_i' \overline{D} Z_i \right) Z_i' \widehat{D} Y_i, \tag{20}$$

where $Z_i = (z_{i1}, z_{i2}, \dots, z_{iT})'$, $z_{it} = (x_{it})'$, $y_i = (y_{i1}, y_{i2}, \dots, y_{iT})'$, $\overline{D} = I_T - \overline{H} (\overline{H}' \overline{H})^{-1} \overline{H}$, $\overline{H} = (h_1, h_2, \dots, h_T)'$, $h_t = (1, \bar{y}_t, \bar{x}_t)$ as the CCE estimators. The CCEMG Group estimator is obtained with the average of the individual CCE estimators as follows:

$$\widehat{B}_{CCEMG} = \sum_{i=1}^N \widehat{B}_{i,CCE} \tag{21}$$

Panel causality analysis

The conventionally used Granger (1969) causality test is inefficient in handling the heterogeneous panel data sets since it assumes the slope coefficient to be homogenous across the individual cross-sectional units. Therefore, following Xu et al. (2021) and keeping into consideration the finding of slope heterogeneity in the data used in this study, the Dumitrescu-Hurlin (2012) panel non-causality method is employed to predict the causal associations between EF and the other macroeconomic determinants of environmental quality. This method is robust to handling both cross-sectional dependency and slope heterogeneity problems and can also be applied for unbalanced panel data sets of any dimensions (Roudi et al. 2019). Both the Granger (1969) and the Dumitrescu-Hurlin (2012) methods predict a test statistic under the null hypothesis of no Granger causality existing between a pair of variables. However, the alternative hypothesis under the Granger (1969) approach states that the Granger causality exists between the pair of variables for all the cross-sectional units since the slope coefficients are assumed to be homogeneous. In contrast, the alternative hypothesis under the Dumitrescu-Hurlin (2012) method states that the Granger causality between the pair of variables exists in at least on the cross-sectional units since the slope coefficients are assumed to be heterogeneous.

This test considers two dimensions of heterogeneity: the heterogeneity of the regression model used to test the Granger causality and the heterogeneity of the causality relationships. This test is used for its additional capacity to provide efficient results for unbalanced panels as it considers cross-section dependence. The heterogeneity of the regression model and the causal relation is considered in the *homogeneous non-causality (HNC)* hypothesis tested by Dumitrescu-Hurlin (2012) test. The HNC hypothesis is employed for the analysis of causality relationships and heterogeneous models. For $T > N$ asymptotic and $N > T$ semi-asymptotic, a distribution was used in the HNC hypothesis. The HNC or the null hypothesis, in this case, is defined as follows:

$$H_0 : \beta_i = 0; \forall i = 1, 2, \dots, N \tag{22}$$

where $\beta_i = (\beta_i^{(1)}, \beta_i^{(2)}, \dots, \beta_i^{(k)})$, although it can change across groups. The non-causality assumption means some of the individual vectors $\beta_i = 0$. The null hypothesis implies there are $N_1 < N$ individual processes with no causality from X to Y. The alternative would be the following:

$$H_1 : \beta_i = 0; \quad \forall i = 1, 2, \dots, N_1 \\ \beta_i \neq 0; \quad \forall i = N_1 + 1, \dots, N \tag{23}$$

where $0 \leq N_1/N < 1$ and N_1 is unknown. As $N_1 = N$ and N_1/N is inevitably less than 1, there is no causality for any of the individuals in the panel, while for $N_1 = 0$ causality is detected for all the individuals in the panel. Under the null hypothesis, the variable X does not Granger cause the variable Y for all the units in the panel. In contrast, when the null hypothesis is rejected and $N_1 = 0$, X Granger causes Y for all the panels, thus obtaining a homogeneous result for causality. To test the null hypothesis, Wald statistics ($W_{i,T}$) are computed for each cross-section and then averaged for each individual to determine the panel Wald statistic ($W_{N,T}^{HNC}$).

Dumitrescu-Hurlin (2012) also used the statistic $W_{N,T}^{HNC}$, which has an asymptotic distribution ($T > N$) associated with the null HNC hypothesis and is defined as:

$$W_{N,T}^{HNC} = \sqrt{\frac{N}{2K}} \left(W_{N,T}^{HNC} - K \right) \tag{24}$$

The statistic W_N^{HNC} , which has a semi-asymptotic distribution ($T < N$) associated with the null HNC hypothesis, is defined as:

$$W_N^{HNC} = \frac{\sqrt{N \left[W_{N,T}^{HNC} - N^{-1} \sum_{i=1}^N E(W_{i,T}) \right]}}{\sqrt{N^{-1} \sum_{i=1}^N Var(W_{i,T})}} \tag{25}$$

Panel causality is therefore estimated for each cross-section through the Dumitrescu and Hurlin (2012) test, and test statistic averages are generated. Two variables are tested in the pair-wise causality test, and the expected results are whether there is unidirectional causality ($X \rightarrow Y$ or $Y \rightarrow X$), bidirectional causality ($X \leftrightarrow Y$) or no causality ($X \neq Y$).

Results and discussion

This section begins by analyzing the results from the CIPS and CADF unit root tests. The corresponding results, as reported in Table 4, reveal all the variables are stationary at their first difference. The statistical significance of the predicted test statistics affirms the stationarity of all the variables. Hence, the overall findings from the panel unit root analysis suggest a

Table 4 The panel unit root results

	CIPS test		CADF test	
	Level	First difference	Level	First difference
lnEF	-2.134	-4.089*	-4.344*	-5.891**
lnGDP	-1.839	-3.271*	-2.204	-4.521***
lnREC	-1.444	-3.457*	-1.418	-5.009**
lnTI	-1.742	-3.813*	-2.874**	-5.464***
lnFD	-2.736	-3.818*	-2.983**	-5.674**
lnPG	-3.317*	-4.011*	-1.386	-2.984***

***indicates significance at 1%; **indicates significance at 5%; *indicates significance at 10%

common order of integration among the variables. The unit root analysis is followed by the panel cointegration analysis.

Table 5 reports the results from the Westerlund (2007) cointegration analysis. The statistical significance, a 1% level, of the four test statistics certifies the presence of cointegrating equations in the model. Hence, it can be said that there are long-run associations between EF, economic growth, renewable electricity generation capacity, technological innovation, financial development, and population growth in the context of the selected ASEAN countries. The affirmation of the long-run relationships fulfills the pre-requisite to predict the long-run elasticities of EF. The regression analysis follows the panel cointegration analysis.

Table 6 reports the short- and long-run elasticities of EF from the CS-ARDL analysis. The results show that economic growth exerts adverse environmental impacts both in the short- and the long run. However, compared to the short-run, the long-run environmental impact of economic growth is found to be relatively smaller. A 1% rise in the per capita real GDP level increases the per capita EF by 0.564% and 0.293% in the short- and long-run, respectively, ceteris paribus. On the other hand, the elasticity estimates show that higher renewable electricity generation capacities contribute to environmental improvement in the selected ASEAN economies. A 1% increase in the renewable electricity generation capacity of the ASEAN economies is found to reduce the per capita EF by 0.110% and 0.120% in the short- and long-run, respectively, ceteris paribus. Besides, the elasticity estimates also reveal the favorable environmental effects of technological innovations in the selected ASEAN countries. Moreover,

Table 5 The Westerlund (2007) cointegration test results

Test statistic	Value	P value
Gt	-25.526***	0.000
Ga	-37.568***	0.000
Pt	-228.487***	0.000
Pa	-127.797***	0.000

***indicates significance at 1%

Table 6 The CS-ARDL elasticity estimates

Variables	Coefficient	St. error	P value
Panel A: Short-run analysis			
lnGDP	0.564**	0.252	0.025
lnREC	-0.110***	0.033	0.001
lnTI	-0.019**	0.008	0.028
lnFD	0.065**	0.029	0.025
lnPG	0.213**	0.228	0.035
ECT _{t-1}	-0.658***	0.058	0.001
Panel B: Long-run analysis			
lnGDP	0.293**	0.124	0.018
lnREC	-0.120**	0.005	0.027
lnTI	-0.065***	0.021	0.003
lnFD	0.037**	0.016	0.020
lnPG	-0.013**	0.130	0.032

*** indicates significance at 1%; ** indicates significance at 5%; *indicates significance at 10%

the long-run marginal impacts are found to be greater than the corresponding short-run impacts. A 1% rise in the number of patent applications is found to reduce the per capita EF by 0.019% and 0.065% in the short- and long-run, respectively, ceteris paribus.

As far as the environmental impacts of financial development are concerned, the elasticity estimates show that financial development is detrimental to the environmental quality in the selected ASEAN countries. The positive signs of the corresponding short- and long-run elasticity estimates affirm this claim. A 1% rise in the share of domestic credit extended to the private sector in the GDP of the ASEAN nations is predicted to increase the per capita EF by 0.065% and 0.037% in the short- and long-run, respectively ceteris paribus. However, the comparatively smaller long-run elasticity implies that in the long run, the financial development policies of these ASEAN countries are likely to become relatively greener. Consequently, the adverse environmental impacts of financial development are seen to be reduced in the long run. Lastly, the elasticity estimates show that although higher population growth initially exerts ecological pressures in the selected ASEAN countries, as the population keeps on increasing, the adverse environmental impacts are seen to decline. A 1% rise in the population growth rate is found to increase the per capita EF by 0.213% in the short run, but in the long run, it reduces the per capita EF by 0.013%, ceteris paribus.

To check for the robustness of the long-run findings, the AMG and CCEMG estimators are also used to predict the long-run elasticities. The elasticity estimates from the robustness analysis are reported in Table 7. The signs of the long-run elasticities of EF associated with economic growth, renewable electricity generation capacity, and technological innovation are seen to be homogenous across all the three regression

Table 7 Robustness analysis

Variables	Augmented Mean Group (AMG)			Common Correlated Effects (CCEMG)		
	Coefficient	St. error	P value	Coefficient	St. error	P value
lnGDP	2.321*	1.383	0.093	0.100**	0.303	0.041
lnREC	- 0.422*	0.251	0.091	- 0.272***	0.104	0.009
lnTI	- 0.176**	0.127	0.063	- 0.017*	0.010	0.098
lnFD	0.159	0.364	0.066	0.058	0.082	0.048
lnPG	0.104	0.906	0.091	0.106	0.163	0.051

*** indicates significance at 1%; ** indicates significance at 5%; * indicates significance at 10%

estimators used in this study. However, under the AMG and CCEMG analyses, the elasticity parameters of EF associated with financial development and population growth are found to be statistically insignificant. These findings provide support to the decision to use the CS-ARDL method, which, in comparison to the AMG and CCEMG estimators, is claimed to be relatively more efficient in handling the cross-sectional dependency and slope heterogeneity issues in the data. The panel causality analysis follows the regression analyses. Figure 3 provides a graphical illustration of the findings from the regression analysis.

Table 8 reports the findings from the Dumitrescu-Hurlin (2012) causality analysis. The findings highlight that EF have bidirectional causal associations with economic growth, renewable electricity generation capacity, technological innovation, financial development, and population growth in the context of the selected ASEAN countries. Hence, these causality findings resonate with the theoretical background of the United Nations SDG declarations, which highlight the importance of simultaneously ensuring economic, social, and environmental sustainability across the globe. Figure 4 graphically illustrates the findings from the causality analysis. Additional causality relations among the other variables are reported in Table 9 in the appendix.

Discussions

The finding of economic growth exerting adverse environmental impacts in the ASEAN-5 countries implies that these nations are yet to prioritize environmental welfare over economic gains. Consequently, despite flourishing economically, the environmental attributes in the respective countries have persistently declined. However, the relatively smaller long-run elasticities suggest that the adverse environmental impacts associated with economic growth tend to decrease as the per capita level of real GDP of these nations continues to increase. In line with this finding, it can be said that as the affluence level of the ASEAN-5 nations increase, there is a tendency to make use of relatively environmentally-friendly inputs for producing the national output, thus coinciding with the views of Brizga et al. (2013). Besides, although the results do not provide concrete evidence of a non-linear inverted U-shaped relationship between economic growth and EF, the EKC hypothesis can be said to hold in the context of the ASEAN countries since the long-run environmental adversities are relatively less. This assertion coincides with the findings in the study by Narayan and Narayan (2010), in which the authors found evidence of the long-run adverse environmental impacts of economic growth to be lower than the short-run impacts in the context of 43 developing economies. The positive economic growth-EF nexus, both in the short- and long run, was

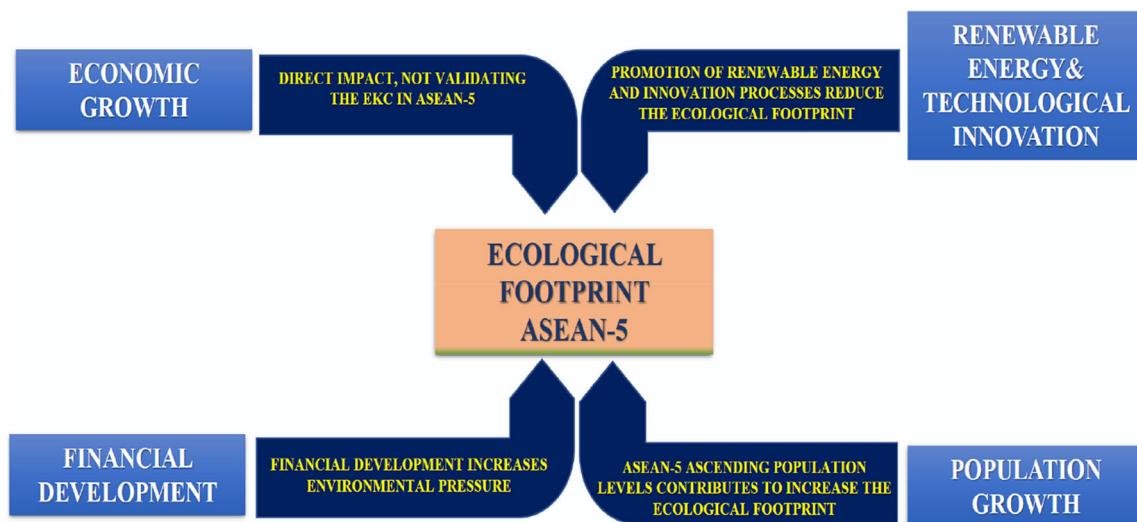


Fig. 3 Graphical scheme main empirical results

Table 8 The results from the Dumitrescu and Hurlin (2012) causality analysis

Null hypothesis	W-stat.	Z-bar stat.	Prob.	Conclusion
lnGDP does not homogeneously cause lnEF	3.110***	3.336	0.001	lnGDP ↔ lnEF
lnEF does not homogeneously cause lnGDP	91.623***	143.288	0.000	
lnREC does not homogeneously cause lnEF	2.1317*	1.7894	0.074	lnREC ↔ lnEF
lnEF does not homogeneously cause lnREC	12.388***	18.006	0.000	
lnTI does not homogeneously cause lnEF	4.715***	5.875	0.000	lnTI ↔ lnEF
lnEF does not homogeneously cause lnTI	19.041***	28.526	0.000	
lnFD does not homogeneously cause lnEF	1.513***	0.812	0.042	lnFD ↔ lnEF
lnEF does not homogeneously cause lnFD	1.053*	0.084	0.094	
lnPG does not homogeneously cause lnEF	2.946***	3.077	0.000	lnPG ↔ lnEF
lnEF does not homogeneously cause lnPG	28.604***	43.647	0.000	

*** indicates significance at 1%; * indicates significance at 10%

also put forward by Nathaniel et al. (2019). However, the authors found the long-run elasticity to be higher than the short-run elasticity in the context of South Africa. Hence, these contrasting findings suggest that the ASEAN countries, as opposed to South Africa, have managed to reduce their EF as their respective national income levels increased.

On the other hand, the finding of higher renewable electricity generation capacity being effective in reducing the EF implies that undergoing renewable energy transition is the ultimate solution for the ASEAN-5 countries for reinstating environmental well-being. This is an extremely important finding because all the 5 Southeast Asian nations considered in this study are predominantly fossil fuel-dependent when it comes to generating electricity. The existing power plants in these countries are monotonically reliant on fossil fuel supplies which exerts significant pressure on the extraction of these resources and also results in emissions of GHG into the atmosphere. Conversely, transitioning from the use of fossil fuels to renewables can resolve these issues and, therefore, be expected to safeguard the environment in the ASEAN-5 nations. The short- and long-run environmental welfare impacts of renewable electricity were also found in the existing study by Bento and

Moutinho (2016) for Italy. Besides, in the context of the top-15 CO₂-emitting economies, Usman et al. (2021) recently claimed that enhancing renewable energy utilization is effective in reducing the EF in the long run. However, these findings are in partial disagreement with the findings reported in the study by Nathaniel and Khan (2020) where the authors showed an insignificant effect of renewable energy consumption on the EF figures of the ASEAN countries. Hence, these contrasting findings provide the justification behind our decision of exploring the renewable energy use-EF nexus from the production-side channel using the renewable energy generation capacity as an indicator of renewable energy use in the ASEAN-5 countries.

Moreover, in the era of the Fourth Industrial Revolution, the finding of technological innovations being effective in reducing the EF figures of the ASEAN-5 countries implies that investing in technological development can help these nations to reduce their ecological demands and also enhance the resource use-efficiency levels. Based on this finding, it can be assumed that technological innovation can enable the ASEAN-5 nations to overcome their technological barriers which have traditionally inhibited their respective renewable electricity generation capacities. Since the renewable energy

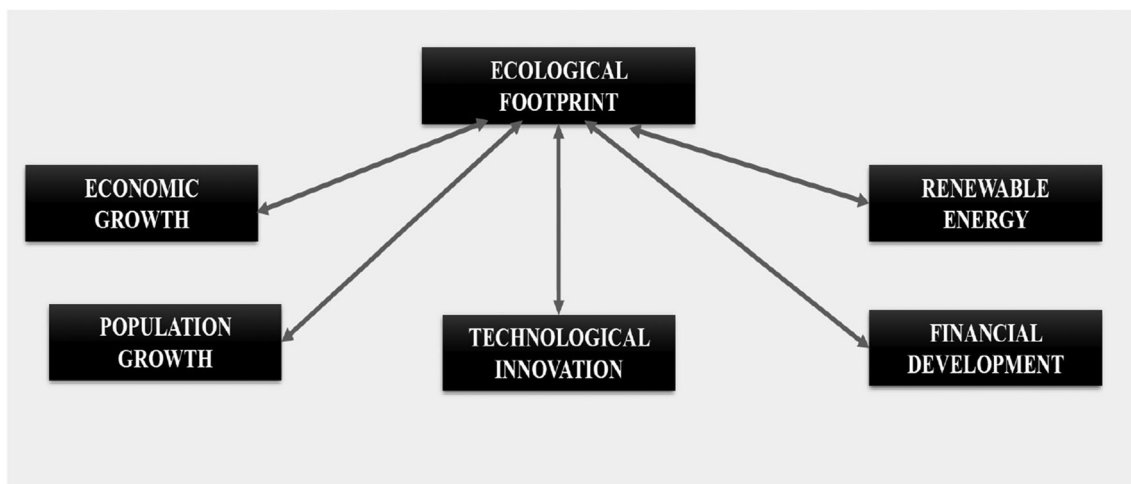


Fig. 4 Dumitrescu-Hurlin EF causality results

power plants, compared to the fossil fuel-based power plants, require the application of contemporary technologies to generate electricity from renewable sources, technological innovation in this regard can be anticipated to facilitate renewable energy transition across Southeast Asia. Similar favorable environmental impacts of technological innovations were reported by Ahmad et al. (2020b) for selected emerging economies. In contrast, Destek and Manga (2021) found that technological innovations cannot explain the variations in the EF figures of the big emerging market economies.

The finding of the positive relationship between EF and financial development implies that financial development policies pursued by the ASEAN-5 countries have not been environmentally friendly. These findings suggest that the loans taken by the private sectors of the ASEAN-5 countries have predominantly been utilized in the development of pollution-intensive industries. Thus, there is scope for the associated governments to develop the financial sector for facilitating the financing of environmentally-friendly projects. Accordingly, financial sector development can be expected to scale up investments within the renewable energy sectors of the ASEAN-5 countries which can be expected to improve the environment further. Similar findings were reported in the existing studies by Baloch et al. (2019) for 59 BRI countries which include the selected ASEAN nations as well. Lastly, the contrasting short- and long-run environmental impacts of population growth indicate that the ecological demand of the population of the ASEAN-5 economies tends to gradually become more ecologically sustainable. Besides, this phenomenon could also be due to the favorable long-run environmental impacts associated with economic growth, expansion in renewable electricity generation capacity, technological innovation, and financial development across these countries.

Conclusion and policy recommendations

The aggravation of environmental quality across Southeast Asia has become a serious concern for the governments of the associated countries. Although the Southeast Asian economies have flourished economically, their growth achievements are believed to have been pinned down, to a certain extent, by the worsening of the environmental attributes within this region. Besides, the recent ratification of the RCEP agreement has raised further concerns for the Southeast Asian economies in respect of the environmental adversities which can accompany the economic growth that is expected to be generated from the execution of this agreement. Furthermore, ensuing environmental sustainability has become critically important for these nations, following their commitments to achieving the SDG and the objectives of the Paris Agreement. Against this backdrop, this paper aimed to model the macroeconomic determinants of environmental quality in the ASEAN-5 countries over the 1985–2016 period. The

environmental quality was analyzed in terms of the EF, which, as opposed to the conventionally used CO₂ emission figures, is believed to be a more comprehensive environmental quality indicator. Among the various macroeconomic variables that are acknowledged to influence the EF figures of the selected ASEAN-5 countries, this study specifically investigated the environmental impacts of economic growth, renewable electricity generation capacity, technological innovation, financial development, and population growth.

The findings from the econometric analysis, in a nutshell, revealed that economic growth is detrimental to environmental quality both in the short- and the long run. However, the long-run impacts were relatively lower, based on which the EKC hypothesis can be said to hold for the selected ASEAN-5 nations. On the other hand, higher renewable electricity generation capacity and technological innovation were seen to improve the environmental quality both in the short and long run. Besides, financial development was estimated to degrade the environment both in the short- and long-run; but, the long-run adverse environmental impacts were seen to be relatively lower. Furthermore, higher population growth was found to deteriorate the environmental quality in the short run while improving it in the long run. Finally, the findings from the causality analysis revealed the bidirectional causal relationships between these variables. In line with these findings, several relevant policies can be recommended.

First, the governments of the ASEAN-5 countries should integrate the environmental development objectives within their respective economic growth policies. As a result, the economic growth of these economies can be sustained without marginalizing the welfare of the environmental attributes. In this regard, it is critically important for these nations to sustainably transform their respective consumption and production processes in an environmentally friendly manner which would not only expedite the economic growth rate but would simultaneously conserve the ecological reserves as well. Therefore, it is pertinent for the ASEAN-5 countries to replace the utilization of unclean resources with cleaner alternatives across all sectors within their respective economies. Second, it is recommended that the ASEAN-5 nations enhance their renewable electricity generation capacities substantially by adopting relevant policies which would facilitate renewable energy transition across the ASEAN region. Therefore, the governments of the ASEAN-5 countries should invest in the development of their respective energy infrastructure to significantly enhance their renewable electricity generation capacities. Besides, investment in research and development can also contribute to renewable energy technology development necessary for generating large-scale electricity outputs from renewable sources.

Third, the government should also incentivize the private sector to undertake investment in research and development for facilitating technological innovation within the ASEAN-5 countries. More importantly, the development of

environmental-related technologies should be encouraged, keeping the objective of ensuring environmental sustainability into consideration. The development of environmental protection-related technologies can be effective in controlling the adverse environmental impacts. It is to be noted that investments in technology can be a credible means of inhibiting the development of the pollution-intensive industries within the selected ASEAN-5 nations. Finally, the selected ASEAN-5 countries should improve their respective financial development policies by integrating the environmental welfare objectives within financial development strategies. It is advised that a relatively higher proportion of total domestic credit extended to the private sector is allotted to the comparatively cleaner industries operating within the ASEAN-5 countries. At the same time, the governments should also subsidize the credits taken for investing in environmentally-friendly projects, which can further reduce the adverse environmental impacts associated with financial development. Furthermore, the governments

should also introduce green bonds to further encourage borrowers to invest in environmentally-friendly projects. Hence, financial development within these countries should ideally be facilitating the green financing initiatives.

Due to data constraints, the analysis conducted in this study was confined to only five of the ten ASEAN states. Besides, data limitation also reduced the period of analysis; consequently, the country-specific analysis could not be performed. As part of the future scope of research, this study can be extended by evaluating the impacts of economic growth, renewable electricity generation capacity, technological innovation, financial development, and population growth on different components of EF. Besides, a sectoral analysis can also be conducted for sector-specific policy-making purposes. Furthermore, the indirect impacts of technological innovation on the environmental quality in the ASEAN countries can be explored using interaction terms within the model.

Appendix

Table 9 Additional results from the Dumitrescu-Hurlin panel causality analysis

Null hypothesis	W-stat.	Z-bar stat.	Prob.	Causality
lnGDP does not homogeneously cause lnEF	3.110***	3.336	0.001	lnGDP ↔ lnEF
lnEF does not homogeneously cause lnGDP	91.623***	143.288	0.000	
lnREC does not homogeneously cause lnEF	2.1317*	1.7894	0.074	lnREC ↔ lnEF
lnEF does not homogeneously cause lnREC	12.388***	18.006	0.000	
lnTI does not homogeneously cause lnEF	4.715***	5.875	0.000	lnTI ↔ lnEF
lnEF does not homogeneously cause lnTI	19.041***	28.526	0.000	
lnFD does not homogeneously cause lnEF	1.513***	0.812	0.042	lnFD ↔ lnEF
lnEF does not homogeneously cause lnFD	1.053*	0.084	0.094	
lnPG does not homogeneously cause lnEF	2.946***	3.077	0.000	lnPG ↔ lnEF
lnEF does not homogeneously cause lnPG	28.604***	43.647	0.000	
lnGDP does not homogeneously cause lnREC	5.6449***	7.3442	0.0000	lnGDP ↔ lnREC
lnREC does not homogeneously cause lnGDP	0.9472***	-0.0835	0.0000	
lnGDP does not homogeneously cause lnTI	2.0090	1.5954	0.1106	lnTI → lnGDP
lnTI does not homogeneously cause lnGDP	5.5504***	7.1948	0.0088	
lnGDP does not homogeneously cause lnFD	3.1396***	3.3831	0.0007	lnGDP → lnFD
lnFD does not homogeneously cause lnGDP	1.9528	1.5064	0.1320	
lnGDP does not homogeneously cause lnPG	4.2049***	5.0675	0.0000	lnGDP ↔ lnPG
lnPG does not homogeneously cause lnGDP	3.5190***	3.9828	0.0001	
lnREC does not homogeneously cause lnTI	2.1569*	1.8292	0.0674	lnREC ↔ lnTI
lnTI does not homogeneously cause lnREC	2.2361**	1.9545	0.0506	
lnREC does not homogeneously cause lnFD	1.6198	0.9799	0.3271	lnREC ≠ lnFD
lnFD does not homogeneously cause lnREC	1.2286	0.3614	0.7178	
lnREC does not homogeneously cause lnPg	3.5227***	3.9887	0.0001	lnREC → lnFD
lnPG does not homogeneously cause lnREC	1.7874	1.2450	0.2131	
lnTI does not homogeneously cause lnFD	2.8318***	2.8963	0.0038	lnTI → lnFD
lnFD does not homogeneously cause lnTI	1.1281	0.2025	0.8395	
lnTI does not homogeneously cause lnPG	5.8966***	7.7421	0.0000	lnPG ↔ lnTI
lnPG does not homogeneously cause lnTI	4.4587***	5.4687	0.0000	
lnFD does not homogeneously cause lnPG	3.9635	4.6857	0.0000	lnPG ↔ lnFD
lnPG does not homogeneously cause lnFD	2.4317	2.2637	0.0236	
lnPG does not homogeneously cause lnFD	2.4317**	2.2637	0.0236	lnPG ↔ lnGDP
lnFD does not homogeneously cause lnPG	3.9635***	4.6857	0.0000	

*** indicates significance at 1%; * indicates significance at 10%

Author contribution AZ conceptualized, conducted the econometric analysis, and wrote the introduction. DB conceptualized, conducted the econometric analysis, and supervised the work. MM analyzed the findings, conducted the literature review, wrote the conclusions and recommendations, and compiled the overall manuscript.

Data availability The data sets used during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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