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RESEARCH ARTICLE

How effective are renewable energy, tourism, trade openness, and foreign direct investment on CO_2 emissions? An EKC analysis for ASEAN countries

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Abstract
The effects of renewable energy, tourism, foreign direct investment, and income on environmental degradation have attracted the attention of many researchers, but to date, no researcher has examined the concurrent effects of these variables on CO_2 emissions for the Association of Southeast Asian Nations (ASEAN) countries. Motivated by this gap in the literature, this study aims to analyze the determinants of carbon dioxide (CO_2) emissions under the environmental Kuznets curve (EKC) hypothesis for six ASEAN countries. To this end, the study utilizes the panel ARDL estimator and the Dumitrescu-Hurlin panel causality test from 1995 to 2018. The results show that (i) tourism and foreign direct investment increase CO_2 emissions. (ii) Real income and trade openness reduce environmental degradation. (iii) Since the long-run income elasticity is lower than the short-run, the EKC hypothesis is valid. (iv) Renewable energy reduces carbon emissions only in the short term and has no effect on environmental quality in the long term. There is also no causal relationship between renewable energy and environmental degradation. This could be due to the ineffective deployment of renewable energy in ASEAN countries. Based on these results, this study suggests that ASEAN countries should effectively use renewable energy, reduce the amount of fossil energy in the tourism sector, and support economic development to achieve a sustainable environment.

Keywords Carbon emissions · EKC · FDI · Tourism · Trade openness · PHH · Renewable energy

Introduction

Although continental drift that has occurred during geologic periods about 4.5 billion years old has caused some changes on Earth, global warming is not as much of a concern as it was in the last century (Koeberl 2006). The use of fossil fuels, which began with the Industrial Revolution, has led to pollution and thus global warming. Ecological degradation and the 1973 oil crisis prompted countries to seek new sources of energy. In this context, renewables, which do not pollute the environment, are beginning to be seen as a solution to environmental concerns and energy security.

Policymakers have been drawn to the adverse effects of modern life on the environment and to the development of environmental awareness (Zameer and Yasmeen 2022). Climate scientists acknowledge that anthropogenic emissions are detrimental to humanity and natural ecosystems (Wei and Lihua 2022). The main cause of global warming is greenhouse gas emissions. Approximately two-thirds of greenhouse gasses (GHGs) are produced by the energy sector (IEA 2017). Carbon dioxide (CO_2) emissions account for about 81% of total GHGs.

The rising temperature has forced international organizations to take stronger steps, and in recent years, policymakers and academics have drawn more attention to issues related to climate change and CO_2 emissions (Zameer et al. 2021). Anthropogenic CO_2 emissions increase global temperature by trapping heat in the atmosphere, and GHGs increased 3.6 times between 1961 and 2011 (IPCC 2014). GHGs, which maintain the earth's temperature at a certain level so that

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living things can survive, are produced by intensive fossil fuels consumption and lead to problems of global warming and climate change (Armeanu et al. 2021). These problems are among the most important and in need of solutions in the 21st century (Gozgor 2017).

The United Nations (UN) has taken many international initiatives to reduce GHGs. Due to concerns about global warming and climate change, various international activities and agreements such as the 1972 Stockholm Conference, the 1987 Brundtland Report, the 1997 Kyoto Protocol, and the 2015 Paris Conference have been implemented to take action to eliminate pollution. The Paris Conference recommended that participating countries move their industrial structures away from petrochemicals and fossil fuels, which cause major environmental challenges (Yasmeen et al. 2020). Besides, the IPCC report (IPCC 2014) stipulates that GHG emissions should be reduced by 50–85% by 2050 compared to the year 2000 in order to prevent this environmental catastrophe. The World Energy Outlook (2020) report also shows that many countries and companies have committed to net zero carbon emissions by 2050. However, due to the high cost of alternative and clean energies, many countries continue to use fossil fuels. Therefore, some countries are in conflict with their goals to achieve the Sustainable Development Goals (SDGs). It is important for the world to comply with the SDGs in the fight against global warming and climate change (Sharif et al. 2020). SDG-13 and SDG-7 are directly related to promoting renewable energy and reducing CO_2 emissions.

A number of rigorous steps have been taken to identify various measures aimed at reducing the negative impact of exhaustible and polluted energy sources by resorting to renewable energy (Steve et al. 2022). However, despite the numerous actions of global organizations, man-made pollution continues to increase (Caglar et al. 2022). Therefore, it is important to analyze the factors affecting these environmental problems to prevent global warming and climate change. Given this importance, this study aims to analyze income, renewable energy consumption, FDI, tourism, and trade openness for potential impacts on CO_2 emissions.

The production process, using a high proportion of fossil fuels for economic growth and development, has resulted in pollution over time. As income levels rise, pollution may increase initially, but as the process progresses, income may play a role in environmental quality. We investigate this situation by comparing short- and long-term income elasticities in the framework of Narayan and Narayan (2010).

After income, energy is one of the most influential variables in the environment. Energy consumption is an indispensable factor of production for economic development through the direct production process (Pata 2018). However, while energy derived from fossil fuels is expected to have an increasing effect on CO_2 emissions, renewable sources are expected to have a reducing effect.

Tourism, which is a rapidly growing sector, contributes to economic growth by enabling the development of urbanization and industrialization. Tourism is also directly related to environmental pollution and global warming (Akadiri et al. 2020). This sector accounts for 8% of GHG emissions globally (Lee et al. 2021). Many touristic activities, such as transportation and accommodation, can adversely affect the environment.

The lack of capital in developing countries causes many macroeconomic problems. To solve these problems, countries need foreign loans or foreign direct investment (FDI). Developing countries can tighten their environmental laws and prioritize economic growth to attract FDI. In a sense, emerging countries may become pollution havens, and in this case, FDI may be a factor that triggers environmental degradation. Similarly, higher trade openness in a country may also result in more CO_2 emissions because of increased industrial production, consumption, and energy usage (Pata 2019). As the global value chain expands, the environmental losses of countries with open trade relations spread worldwide (Wang et al. 2021).

We analyze the impact of the above determinants of pollution for six ASEAN countries. We selected these countries for the following reasons. First, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam account for 90% of GHG emissions (Adeel-Farooq et al. 2021). Second, the ASEAN region occupies an important position in the world with a population of over 600 million and a GDP of $3.1 trillion (Anwar et al. 2021). This large population and economy can lead to environmental degradation. Figure 1 shows the increase in per capita CO_2 emissions in the six ASEAN countries from 1995 to 2018.

As shown in Fig. 1, Singapore is the only country that has been able to reduce its CO_2 emissions over a period of

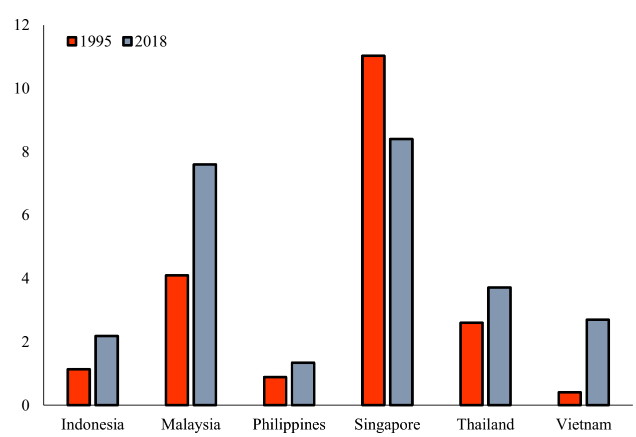

Fig. 1 CO_2 emissions in six ASEAN countries (per capita metric tons). Source: World Bank (2022)

about 25 years. From 1995 to 2018, per capita, CO_2 emissions increased 85% in Malaysia, 92% in Indonesia, and 566% in Vietnam. In Thailand and the Philippines, the rate of increase in environmental degradation is relatively lower. The increasing amount of CO_2 emissions negatively affects the environmental quality and living beings (Wei and Lihua 2022). The fact that CO_2 emissions continue to increase in five of the six ASEAN countries shows that these countries are contributing to global warming and climate change.

The ASEAN Community promotes a sustainable society that supports environmental protection in Vision 2025 (ASEAN 2015). The use and diversification of renewables plays a vital function in SDG-7. However, ASEAN countries are underutilizing renewable resources. This situation is illustrated in Fig. 2.

As seen in Fig. 2, the share of renewable resources in total energy has declined in four ASEAN countries, with the exception of Thailand and Singapore. These countries have increased the weight of fossil fuels for economic development, which has led to an increase in CO_2 emissions. Therefore, our study seeks answers to several research questions. (i) Is current renewable energy sufficient to improve environmental conditions in ASEAN countries? (ii) Can an increase in income help reduce CO_2 emissions? (iii) Do FDI and trade openness have a compounding impact on pollution? We explore the answers to these questions by accounting for the possible cross-sectional dependence (CSD) in the panel data and using the panel ARDL approach.

This study makes two important contributions to the current literature. (i) This is the first study to utilize the approach of Narayan and Narayan (2010) to analyze the validity of the PHH and EKC hypothesis in ASEAN countries, taking into account multicollinearity issues. (ii) The study is the only attempt to analyze the effects of tourism, income, renewable energy, trade openness, and FDI on CO_2 simultaneously for the ASEAN region. Thus, our study is

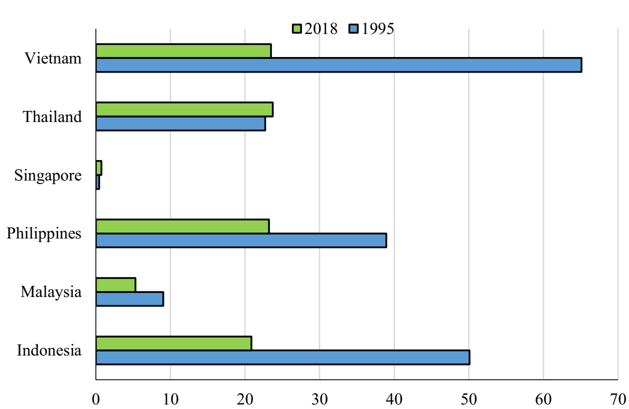

Fig. 2 Renewable energy share in the total energy mix in ASEAN countries (% of total). Source: World Bank (2022)

expected to provide new and robust insights on policy measures to reduce CO_2 emissions for ASEAN countries.

The remainder of the study is organized as follows: "Theoretical perspective and related literature" presents the theoretical perspective of the study and the related literature. "Data, model, and methodology" contains the model and methodology. "Results and discussion" shows and discusses the results, and the "Conclusions" concludes the study.

Theoretical perspective and related literature

Theoretical perspective

Researchers investigate the effects of income and FDI on environmental degradation using the environmental Kuznets curve (EKC) and pollution haven hypothesis (PHH), respectively. Whether these two hypotheses are valid between countries or groups of countries continues to be widely debated today.

The basis of the EKC hypothesis is slightly older than the PHH. Kuznets (1955) investigated the existence of an inverted U-shaped relationship between per capita income and income inequality. In the literature, this relationship is referred to as the Kuznets curve. Environmental economists, inspired by this curve, established the EKC hypothesis, which examines the relationship between pollution and income. The EKC hypothesis began with studies by Grossman and Krueger (1991, 1995), and numerous studies have been conducted in this area in the literature (Stern et al. 1996; Isik et al. 2020; Pata and Hizarci 2022).

Figure 3 illustrates the EKC hypothesis graphically. By shifting from agriculture to industry, the consumption of natural resources exceeds their regenerative capacity, waste is generated and toxins are produced, all of which can contribute to pollution and emissions. Economic development entails massive use of resources, causing serious environmental degradation (Zameer et al. 2020a). After the turning point indicated by the orange arrow, the acceleration of economic development contributes to the development of the knowledge-intensive service sector, increased environmental awareness, health spending and technology investment, and the implementation of better environmental regulations (Dinda 2004).

The EKC hypothesis implies a nonlinear link between income and environmental degradation; in other words, income becomes an environmentally friendly element over time. In the test of the EKC hypothesis created in quadratic form, the square of the GDP variable is usually included in the model. However, such an add-on can cause multicollinearity problems and inconsistent estimates. Stern (2004) emphasized that studies analyzing the EKC hypothesis as a

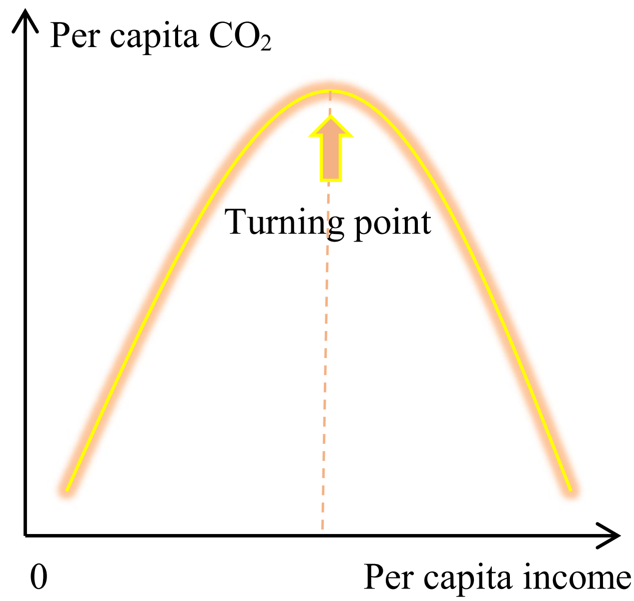

Fig. 3 Representation of the EKC

quadratic model are econometrically weak. To help solve this problem, Narayan and Narayan (2010) advocate comparing income elasticities. In this approach, since the square of GDP is not included in the model, the multicollinearity problem is avoided.

The literature section of the study consists of five separate subsections. First, the studies that analyze the EKC hypothesis are discussed. The second subsection describes studies that examine the impact of renewable energy on CO_2 emissions. The third subsection summarizes the studies that examine the impact of FDI on the environment, and the fourth subsection investigates the relationship between tourism and pollution. Finally, the fifth subsection presents studies investigating determinants of CO_2 emissions and similar pollutants for ASEAN countries.

Related literature

Researchers have shown great interest in the EKC hypothesis, and their results differ widely in terms of model, variables, and approaches (Shahbaz and Sinha 2019). However, a limited number of studies focused on the approach of Narayan and Narayan (2010). Even among these studies, there is no consensus.

Among the studies that tested the EKC hypothesis, Narayan and Narayan (2010) conducted a panel Pedroni cointegration test for CO_2 emissions for 43 developing countries and reported that income elasticity is higher in the short run than in the long run for about 35% of the sample. Jaunky (2011) employed system generalized methods of moments for 36 developed countries and noted that income elasticities do not support an EKC. Al-Mulali et al. (2016) utilized the ARDL estimation for Kenya and argued that the EKC exists for CO_2 emissions. Gokmenoglu and Taspinar (2016) performed the ARDL method and verified the EKC for CO_2 emissions in Turkey. Saboori et al. (2016) utilized the ARDL approach for 10 countries OPEC and noted that in six of them, the long-term income elasticity for CO_2 emissions is lower than in the short run. Dong et al. (2018) used the same method and supported the EKC in China for CO_2 emissions. Zambrano-Monserrate et al. (2018a) applied an ARDL model for Peru, and their results do not support the EKC relationship. Yilanci and Pata (2020) used the Fourier ARDL cointegration test and did not verify the hypothesis in China for ecological footprint. Pata and Isik (2021) used the novel dynamic ARDL approach in China and confirmed the EKC hypothesis. Pata and Balsalobre-Lorente (2022) applied the novel dynamic ARDL approach to Turkey and found that income elasticities represent an EKC relationship for the load capacity factor.

Taking a close look at the above studies, we see that the results vary based on the environmental variables, the countries or groups of countries studied, and the methods used. These studies do not clearly establish the validity of the EKC, and no study applies this approach to ASEAN countries.

Many studies examine the renewables-CO_2 emissions nexus. These studies have generally proven that renewable energy is environmentally friendly (Balsalobre-Lorente et al. 2021). However, a few studies have emphasized that renewable resources do not have a pollution-reducing effect and the reason is ineffective or inadequate utilization (Pata and Caglar 2021).

Foreign direct investment can contribute to the growth-pollution nexus through two channels. First, FDI can lead to an increase in national output, which increases pollution, implying the validity of the PHH. Second, a reduction in pollution can be achieved through the use of more efficient production technologies thanks to FDI (Lau et al. 2014). There is no clear consensus among studies on the relationship between FDI and the environment. Some studies suggest that FDI increases environmental degradation; the PHH hypothesis is valid (Rahaman et al. 2022), while others argue the opposite (Zhang et al. 2022).

The impact of tourism on pollution is also a controversial issue. While some researchers emphasize that tourism degrades environmental quality and increases pollution (Selvanathan, 2021), others claim that tourism revenues and the tourism sector can help improve environmental conditions (Wei and Lihua 2022).

Details of the studies that examined the effects of renewable energy, FDI, and tourism on CO_2 emissions are shown in Table 1. As can be seen, there is no consensus on the role of these determinants on CO_2 emissions.

Table 1 Summary of the environmental literature on renewable energy, FDI, and tourism

Common findings	Work	Period	Countries	Approach
Panel (a) Renewable energy				
Studies indicating that REC reduces environmental degradation	Danish et al. (2017)	1970–2012	Pakistan	ARDL, DOLS, FMOLS
	Zafar et al. (2019)	1990–2015	18 emerging economies	Pedroni cointegration
	Koc and Bulus (2020)	1971–2017	South Korea	ARDL
	Sharif et al. (2020)	1965q1–2017q4	Turkey	Quantile ARDL
	Balsalobre-Lorente et al. (2021)	1995–2015	Portugal, Italy, Greece and Spain	Pedroni cointegration, FMOLS
	Mehmood (2021)	1990–2017	Pakistan, India, Bangladesh, and Sri Lanka	CS-ARDL
	Bekun (2022)	1990–2016	India	Johansen cointegration, FMOLS, DOLS
	Haldar and Sethi (2022)	2000–2018	16 emerging countries	Driscoll-Kraay Panel Corrected Estimators
	Rahman et al. (2022)	1990–2018	12 developed countries	NARDL
Studies claiming that renewable energy has no significant impact on the environment	Lin and Moubarak (2014)	1977–2011	China	ARDL
	Al-Mulali et al. (2015)	1981–2011	Vietnam	ARDL
	Pata (2018)	1974–2014	Turkey	ARDL, Gregory-Hansen cointegration
	Pata and Caglar (2021)	1980–2016	China	Augmented ARDL
Panel (b) FDI				
FDI increases environmental degradation, PHH is valid	Lau et al. (2014)	1970–2008	Malaysia	ARDL
	Khan and Ozturk (2020)	1980–2014	17 Asian countries	Pedroni cointegration, FMOLS
	Pata and Kumar (2021)	1980–2016	China and India	Bootstrap ARDL
	Rahaman et al. (2022)	1990–2019	Bangladesh	ARDL
FDI mitigates environmental pollution	Tsaurai (2019)	2003–2014	12 West African countries	Pooled OLS
	Zameer et al. (2020b)	1985–2017	India	ARDL
	Bhujabal et al. (2021)	1990–2018	18 Asia Pacific countries	Westerlund cointegration, PMG
	Agboola et al. (2022)	1970–2020	Turkey	Dynamic ARDL
	Zhang et al. (2022)	1996–2019	BRICS	NARDL
Panel (c) Tourism				
	Solarin (2014)	1972–2010	Malaysia	ARDL
	Uzuner et al. (2020)	1970–2014	Turkey	Asymmetric causality
	Andlib and Salcedo-Castro (2021)	1995–2019	4 South Asian countries	Pedroni cointegration, FMOLS, DOLS
Tourism ravages the environment.	Selvanathan et al. (2021)	1990–2014	5 South Asian countries	ARDL
	Bin Amin and Aftabi Atique (2021)	1995–2019	5 South Asian countries	Durbin-Hausman cointegration, Panel ARDL
	Muhammad et al. (2021)	2002–2014	13 Muslim countries	Panel cointegration tests and estimators
Tourism is an environmentally friendly industry	Shakouri et al. (2017)	1995–2013	12 Asia Pacific countries	GMM
	El Menyari (2021)	1980–2014	4 North African countries	Westerlund cointegration, dynamic seemingly unrelated regression
	Rahaman et al. (2022)	1990–2019	Bangladesh	ARDL
	Wei and Lihua (2022)	1995–2018	6 ASEAN countries	Westerlund and Edgerton cointegration, CS-ARDL

DOLS, dynamic ordinary least squares; *FMOLS*, fully modified ordinary least squares; *CS-ARDL*, cross-sectional ARDL; *NARDL*, nonlinear ARDL; *PMG*, pooled mean group; *GMM*, generalized method of moments

In the final subsection, we examine the studies that focused on ASEAN countries. Chandran and Tang (2013) performed the Johansen cointegration test and found that the EKC hypothesis is invalid for CO_2 emissions in five ASEAN countries. Saboori and Sulaiman (2013) employed ARDL countries and determined that the EKC hypothesis is invalid for three out of five ASEAN countries. Heidari et al. (2015) identified an inverted U-shaped relation between income and CO_2 emissions for five ASEAN countries by applying the panel smooth transition regression. Using various panel cointegration tests and estimators for four ASEAN countries, Liu et al. (2017) found that the EKC is invalid for CO_2 emissions and emphasized the importance of renewable energy for environmental quality development. Salman et al. (2019) used the Westerlund panel cointegration test, and their results showed the validity of the EKC for seven ASEAN countries. Kisswani et al. (2019) applied ARDL and provided no evidence for the EKC hypothesis in five ASEAN countries. Vo et al. (2019) used ARDL and found no evidence of EKC for CO_2 emissions in four of five ASEAN countries. Guzel and Okumus (2020) also examined five ASEAN countries using the Augmented Mean Group Estimator and confirmed the validity of both PHH and EKC. Kongbuamai et al. (2020) used the Driscoll-Krayy panel regression model, and their results supported an inverted U-shaped EKC for ten ASEAN countries. They also found that tourism reduces the ecological footprint. Munir et al. (2020) applied panel fully modified, pooled, and dynamic ordinary least squares estimators and concluded that an inverted U-shaped link exists between CO_2 emissions and income for five ASEAN countries. Anwar et al. (2021) conducted Method of Moments Quantile Regression and various panel data estimators for six ASEAN countries. The results of the study verified the validity of the EKC for CO_2 emissions. Using panel mean and pooled mean group estimators, Adeel-Farooq et al. (2021) affirmed the validity of the EKC for methane emissions in six ASEAN countries and reported the polluting role of trade openness.

The studies examining the EKC hypothesis for ASEAN countries consider different numbers of countries, different empirical methods, and time periods. While seven of the 12 studies were examined to support the validity of the EKC hypothesis, five of them claim the opposite. Almost all of these studies used quadratic models. According to Narayan and Narayan (2010), this may lead to a multicollinearity problem. There is also no consensus among the studies that examine the impact of FDI, tourism, and renewable energy on CO_2 emissions. These two reasons represent research opportunities for us. In other words, the absence of a study in the literature to test the EKC hypothesis for ASEAN countries by considering the multicollinearity problem and the fact that the effects of renewable energy, FDI, income, and trade openness on CO_2 emissions have not been tested simultaneously for this group of countries are important research gaps. In this context, we aim to contribute to the existing literature by testing the validity of the EKC hypothesis for the first time using the procedure of Narayan and Narayan (2010) in six ASEAN countries.

Data, model, and methodology

Data and model

Following the work of Wei and Lihua (2022), we analyze the six ASEAN countries. Using annual data for the period 1995–2018, we test the effects of FDI, GDP, renewable energy, and foreign trade on CO_2 emissions with different panel data methods. Table 2 provides some characteristics and information on the variables, all compiled by the World Bank (2022).

To obtain reliable and consistent results, we transform all series to natural logarithms, but we do not convert the logarithms of FDI because they have negative values. Negative FDI indicates that the outflow of foreign investment is greater than the inflow (Eurostat 2018). In other words, negative FDI implies that the investment value made by foreign investors in a year is less than the investment value withdrawn (UN 2007). Some of the ASEAN countries experience this situation in terms of FDI. Figure 4 shows the course of the FDI and other variables over time.

Singapore has the highest CO_2 emissions, GDP, and TO during 1995–2018, and Vietnam has the highest renewable energy share among ASEAN countries. Among these countries, the Philippines and Vietnam have the lowest real income, while Singapore uses the least renewable energy.

Table 2 Data description

Variables	Abbreviation	Description and measurement
Carbon dioxide emissions	CO_{2it}	Metric tons per capita
Tourism	$TOUR_{it}$	Number of arrivals, thousand person
Foreign direct investment	FDI_{it}	Net inflows (% of GDP)
Real income	GDP_{it}	Constant 2015 US$ per capita
Renewable energy consumption	REC_{it}	% of total final energy consumption
Trade openness	TO_{it}	The ratio of total exports and imports to GDP

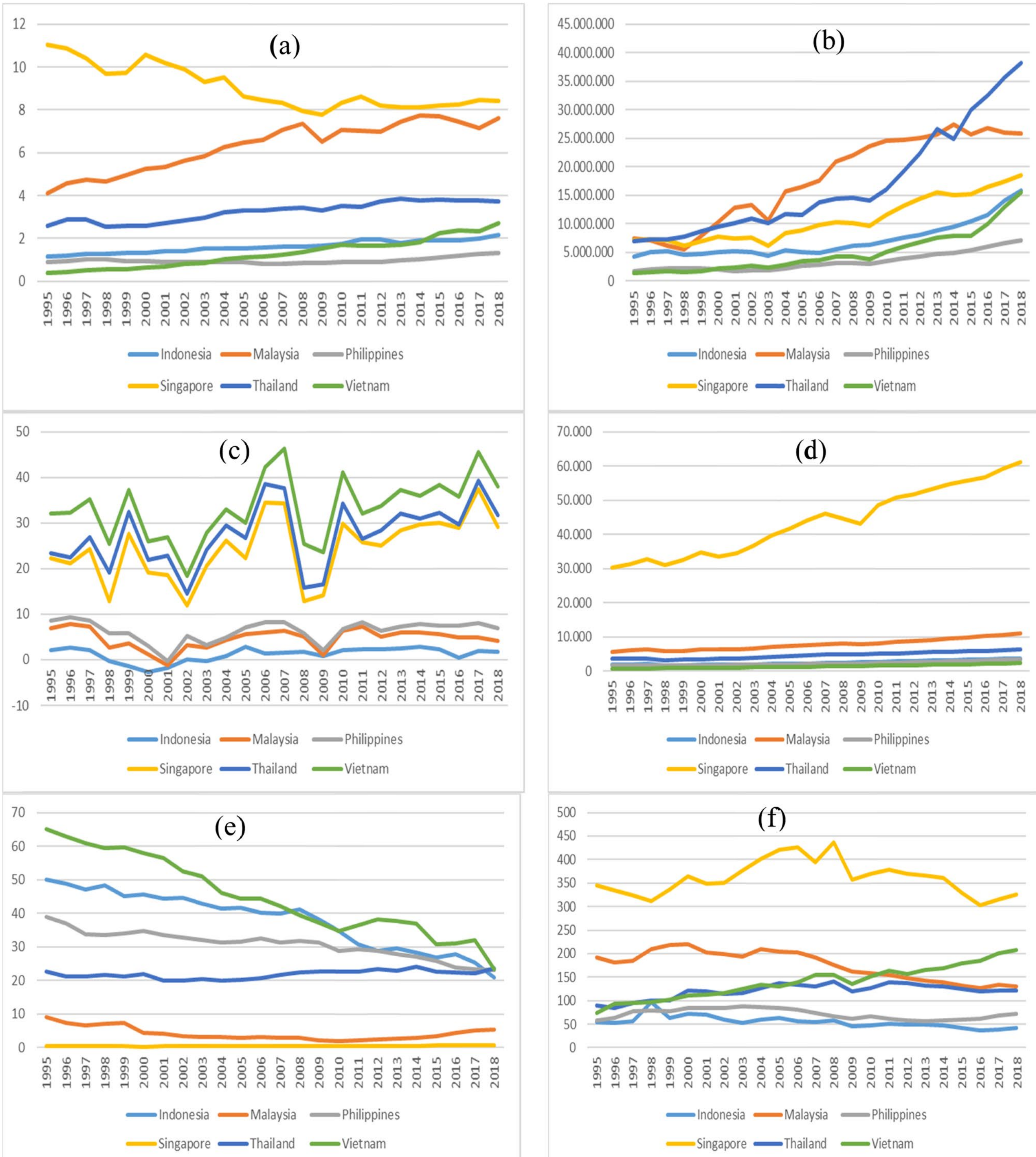

Fig. 4 Plots of variables for the case of ASEAN countries, (**a**) CO_2 emissions per capita, (**b**) tourism (number of arrivals), (**c**) foreign direct investment (% of GDP), (**d**) real income per capita, (**e**) renewable energy, and (**f**) trade openness

After defining the variables, we present some statistics and correlation matrix in Table 3.

The variable with the highest mean value is TOUR, while the variable with the lowest value is CO_2. Since its logarithm is not taken, FDI has the highest standard deviation. The minimum values of REC and FDI are negative, while the other variables are positive. The outputs of the correlation analysis are consistent with the theoretical expectations. We then analyze whether multicollinearity exists among the independent variables by calculating the variance inflation

Table 3 Descriptive statistics and correlation matrix

	$lnCO_2$	lnTOUR	FDI	lnGDP	lnREC	lnTO
Mean	0.414	6.877	5.552	3.675	1.055	2.096
Median	0.408	6.877	3.257	3.545	1.368	2.104
Maximum	1.042	7.581	29.354	4.785	1.813	2.640
Minimum	−0.392	6.130	−2.757	2.863	−0.487	1.573
Std. Dev.	0.386	0.347	6.470	0.502	0.703	0.278
$lnCO_2$	1.000					
lnTOUR	0.773***	1.000				
FDI	0.544***	0.171***	1.000			
lnGDP	0.905***	0.591***	0.735***	1.000		
lnREC	−0.883***	−0.472***	−0.742***	−0.957***	1.000	
lnTO	0.763***	0.376***	0.744***	0.762***	−0.821***	1.000
Observations	144	144	144	144	144	144

***1% level of significance

Table 4 Test for multicollinearity

Variable	Tolerance	VIF
GDP	0.235	4.24
TOUR	0.498	2.00
FDI	0.351	2.84
TO	0.282	3.55
REC	0.240	4.15

factor (VIF) and tolerance values for each variable. Tolerance values of not less than 0.2 and VIF values of less than "5" in Table 4 indicate that there is no multicollinearity.

In this study, we test the determinants of CO_2 emissions with Eq. (1) for six ASEAN countries.

$$CO_{2it} = f\left(TOUR_{it}, FDI_{it}, GDP_{it}, REC_{it}, TO_{it}\right) \quad (1)$$

This functional equation can be converted into Eq. (2) for the elasticity calculation.

$$\begin{aligned} \ln CO_{2it} = & \alpha_0 + \beta_1 lnTOUR_{it} + \beta_2 FDI_{it} + \beta_3 \ln GDP_{it} \\ & + \beta_4 \ln REC_{it} + \beta_5 \ln TO_{it} + e_t \end{aligned} \quad (2)$$

In Eq. (2), CO_2 is carbon dioxide emissions, i is each country in the panel, TOUR is tourism, FDI is foreign direct investment, GDP is gross domestic product, REC is renewable energy consumption, TO is trade openness, t is time period, α is constant term, and $\beta_{1 \text{ to } 5}$ show the coefficient of the explanatory variables. The expectation is that all independent variables except renewables will have a positive effect on pollution. This expectation is based on theoretical foundations and hypotheses.

H1. Tourism leads to more CO_2 emissions.

Theoretically, tourism plays an active role in energy consumption patterns, economic expansion, natural resources, and environmental degradation (Khan et al. 2020). Pigram (1980) established the first theoretical relationship between tourism and the environment. According to Pigram (1980), tourism can cause environmental damage. This negative linear relationship can be very strong or weak. Tourism can increase CO_2 emissions in three ways (Gössling 2002): (I) Tourism infrastructure activities can lead to land changes and generate pollutant emissions. (II) Indirect pressure from tourists on animals and plants can lead to increased emission levels. (III) Tourism transportation generates more CO_2 emissions by increasing the demand for energy resources such as oil and coal.

H2. FDI increases environmental degradation.

FDI can lead to environmental degradation by increasing the activities of pollution-intensive industries (Sapkota and Bastola 2017). The PHH hypothesis states that developed countries shift their polluting production to countries with weak environmental laws, resulting in a negative trade-off between FDI inputs and the environment for developing countries (Cropper and Oates 1992). As Copeland and Taylor (1994) argue, PHH implies that developing countries make soft environmental adjustments to support their economic expansion and upgrade their inadequate infrastructure. Therefore, an increase in FDI may affect the expansion of emissions.

H3. Economic expansion has an effect on pollution.

In the economics literature, the relationship between growth and the environment, particularly pollution and income, is an important topic that has gained prominence in recent years (Brock and Taylor 2005). The economic structure is in the process of transformation toward agriculture, industry, and services. In the first phase of the development process, pollution increases because energy consumption from fossil fuels increases in the transition from the agricultural to the industrial sector, and environmental concerns are not important in this phase. In the transition process to the service sector, the demand for goods and services for environmental goods increases with the higher income level, so the environmental quality can be improved. Grossman and Krueger (1991) and Panayotou (1993) argued that this transformation represents an EKC form with an inverted U-shape (Grossman and Krueger 1991; Panayotou 1993). Narayan and Narayan (2010) revealed that this transformation could be analyzed in linear form. In this approach, environmental degradation can decrease over time if the long-run elasticity of income is lower than the short-run elasticity.

H4. Increasing trade openness accelerates the spread of pollution.

The relationships between trade openness and environmental degradation can be explained by three effects (Grossman and Krueger 1991): (I) The scale effect implies that trade openness increases economic growth and environmental degradation through improved investment and trade liberalization. (II) The composition effect; as trade openness increases for developing countries, imports and exports become profitable and environmental-unfriendly, resulting in an increase in emissions. (III) The technique effect of trade openness shows that developing countries reduce environmental degradation by importing green technologies. For developing countries, scale and composition effects are likely to outweigh the technical impact.

H5. Renewable energy can help mitigate emissions.

Renewable energy is an important solution in the fight against global warming, as it has the function of reducing CO_2 emissions (Shahnazi and Shabani 2021). Countless scientists have recognized that clean and green renewable sources are a helpful factor in reducing greenhouse gas emissions (Vo et al. 2020). Thus, our study examines the hypothesis that renewable energy can reduce CO_2 emissions in ASEAN countries. The above hypotheses explored in the study are summarized graphically in Fig. 5.

To test the validity of these hypotheses, we use panel data approaches. Since both cross-section and time dimensions of the series are handled with panel data analysis, this approach better controls the problems of internality, varying variance, serial correlation, and multicollinearity (Baltagi 2013). In addition, it is possible to obtain better estimation results with panel data analysis (Shoaib et al. 2020).

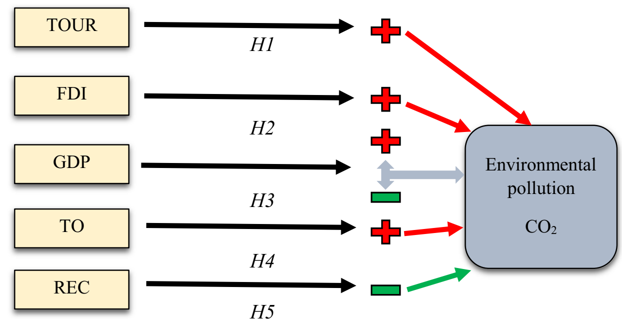

Fig. 5 Conceptual model

Methodology

The study makes use of various panel unit root, cointegration, and causality tests that include CSDs. Analyzing the determinants of CO_2 emissions with different techniques, such as using both panel estimators and causality tests, can provide more effective recommendations for policymakers with robust results.

Panel ARDL-PMG

Pesaran et al. (1999) developed the panel ARDL-pooled mean group (PMG) approach. The main difference of this method from other methods, for example, is that not all series need to be stationary at the same level. The panel ARDL method also provides strong and effective results for small samples (Narayan and Narayan 2004). The panel ARDL-PMG approach considers cross-sectional heterogeneity through short-term parameters (Mensah et al. 2019). The cointegration relationship between variables can be analyzed as follows:

$$\Delta Y_{1,it} = \alpha_{1i} + \beta_{1i} Y_{1,it-1i} + \sum_{l=2}^{k} \beta_{1i} X_{1,it-1} + \sum_{j=1}^{p-1} Y_{1ij} \Delta Y_{1,it-j} + \sum_{j=0}^{p-1} \sum_{l=2}^{k} Y_{1ij} \Delta X_{1,it-j} + \mu_{1,it} \quad (3)$$

Here, Y_1 represents the dependent variable, X_1 is the independent variable, and μ_1 is the error term. When the variables in this study are added to the ARDL model in Eq. (3) and the equation is rearranged:

$$\Delta CO_{2it} = \alpha_{1i} + \beta_{1i} CO_{2it-1} + \beta_{2i} TOUR_{it-1} + \beta_{3i} FDI_{it-1} + \beta_{4i} GDP_{it-1} + \beta_{5i} REC_{it-1} + \beta_{6i} TO_{it-1} + \sum_{j=1}^{p} Y_{1i} \Delta CO_{2it-j} + \sum_{i=o}^{q} Y_{2i} \Delta TOUR_{it-j} + \sum_{i=o}^{q} Y_{3i} \Delta FDI_{it-j} + \sum_{i=o}^{q} Y_{4i} \Delta GDP_{it-j} + \sum_{i=o}^{q} Y_{5i} \Delta REC_{it-j} + \sum_{i=o}^{q} Y_{6i} \Delta TO_{it-j} + \mu_{1,it} \quad (4)$$

In determining the cointegration link between the variables in Eq. (4), the following hypotheses are tested:

$$H_0 : \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = 0; H_1 : \beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq 0.$$

The alternative hypothesis H_1 is tested against the null hypothesis H_0 using the F-test. If the F-statistic is greater than upper critical values $I(1)$, the null hypothesis is rejected. The coefficients of the ARDL model are measured employing the PMG approach.

Panel causality test

The existence of a causality relationship between the series is investigated using the method developed by Dumitrescu and Hurlin (2012). The main advantages of this method are that it takes into account the CSD between the countries that make up the panel (Dumitrescu and Hurlin 2012). In this test, the causality relationship between Y and X is analyzed using a linear model as follows:

$$Y_{i,t} = \alpha_i + \sum_{k=1}^{K} \beta_i^k Y_{i,t-k} \sum_{k=1}^{K} Y_i^k X_{i,t-k} + \varepsilon_{i,t}$$
$$t = 1, 2, \ldots, T; i = 1, 2, \ldots, N \quad (5)$$

In Eq. (5), k represents the optimal lag length. The main limitations of this method are the assumption that the coefficients in the equation are homogeneous and the series must be stationary. The null and alternative hypotheses of the DH causality test can be defined as follows:

$H_0 : \beta_i^{(k)} = 0 \, for \, i$ — No causality relationship from X to Y for all cross-sections.

$H_1 : \begin{matrix} \beta_i^{(k)} = 0 \; i = 1, 2, \ldots N_1, \\ \beta_i^{(k)} \neq 0 \; i = N_1 + 1, N_1 + 2, \ldots N, \end{matrix}$ — Unidirectional causality from X to Y for some cross-sections.

Results and discussion

Cross-sectional dependence results

We first test whether CSD is present in the panel time series data using Breusch-Pagan LM (Breusch and Pagan 1980), bias-corrected scaled LM (Baltagi et al. 2012), and Pesaran's CD (Pesaran 2004) tests. CSD implies that the countries included in the panel data are economically and geopolitically interdependent and that a shock in these countries can affect another country. If CSD is present in the panel data, the results may be biased and inconsistent if methods that take this into account are not used. Therefore, we test for CSD and apply appropriate methods when it is present. Table 5 presents the results of the CSD tests.

The results show that CSD exists for all series except FDI. In other words, a shock in tourism, energy, and trade in one country can affect other countries. For this reason, we use second-generation panel data methods considering CSD.

Panel unit root test results

In our study, the stochastic properties of the series are examined by the panel unit root tests of Levin et al. (2002) (LLC), Im et al. (2003) (IPS), and Pesaran (2007) (cross-sectionally augmented Im-Pesaran-Shin (CIPS)). The results of the unit root tests are shown in Table 6.

According to the LCC unit root test, the FDI and CO_2 are stationary at the level. The IPS test shows that only the FDI series is stationary; all other series contain a unit root. When using the ARDL test, the dependent variable must be $I(1)$. The results of the CIPS test, which does account for CSD, show that only FDI is stationary at level, while all other series are stationary at first difference. Therefore, the use of the panel approach ARDL-PMG is appropriate.

Panel ARDL results

We apply the panel ARDL-PMG approach to examine the determinants of CO_2 emissions. Table 7 presents the panel ARDL-PMG results. The coefficient of ECT is negative and statistically significant. This coefficient implies that short-term deviations will approach the long-term equilibrium with a convergence speed of 22%.

Regarding the relationship between income and the environment, although the GDP coefficient is positive in the short run, it is negative in the long run and statistically significant at the 1% level. In the short run, a 1% increase

Table 5 CSD test results

Variables	Breusch-Pagan LM	Bias-corrected scaled LM	Pesaran CD
$\ln CO_2$	215.820 (0.000)***	36.53 (0.000)***	4.41 (0.000)***
lnTOUR	307.880 (0.000)***	53.34 (0.000)***	17.50 (0.000)***
FDI	16.210 (0.368)	0.09 (0.927)	0.22 (0.825)
lnGDP	344.800 (0.000)***	60.08 (0.000)***	18.56 (0.000)***
lnREC	138.220 (0.000)***	22.36 (0.000)***	−0.11 (905)
lnTO	97.670 (0.000)***	14.96 (0.000)***	2.63 (0.008)***

***Significance at 1% level

Table 6 Panel unit root test results

Tests	Variables	Level		Δ	
		C	C+T	C	C+T
LLC	$lnCO_{2it}$	−2.52(0.005)***	0.08(0.534)	——	−7.38(0.000)***
	$lnTOUR_{it}$	4.35(1.000)	1.90(0.971)	−5.78(0.000)***	−5.59(0.000)***
	FDI_{it}	−3.52(0.000)***	−3.95(0.000)***	——	——
	$lnGDP_{it}$	1.43(0.924)	4.58(1.000)	−19.13(0.000)***	−3.19(0.000)***
	$lnREC_{it}$	1.84(0.967)	0.99(0.839)	−6.92(0.000)***	−6.72(0.000)***
	$lnTO_{it}$	−1.31(0.095)*	0.084(0.533)	−5.99(0.000)***	−3.47(0.000)***
IPS	$lnCO_{2it}$	−0.26(0.394)	0.63(0.735)	−6.04(0.000)***	−6.54(0.000)***
	$lnTOUR_{it}$	5.44(1.000)	2.17(0.985)	−6.20(0.000)***	−8.25(0.000)***
	FDI_{it}	−4.09(0.000)***	−4.80(0.000)***	——	——
	$lnGDP_{it}$	6.36(1.000)	0.16(0.565)	−11.84((0.000)***	−5.88(0.000)***
	$lnREC_{it}$	2.40(0.991)	0.68(0.753)	−6.73(0.000)***	−6.28(0.000)***
	$lnTO_{it}$	−0.36(0.358)	−1.43(0.075)**	−8.04(0.000)***	−6.55(0.000)***
CIPS	$lnCO_{2it}$	−1.29	−0.89	−3.77***	−3.91***
	$lnTOUR_{it}$	−1.97	−1.61	−3.77***	−4.51***
	FDI_{it}	−2.62***	−3.84***	——	——
	$lnGDP_{it}$	−1.59	−1.51	−2.15	−2.84*
	$lnREC_{it}$	0.26	−2.17	−3.44***	−3.26
	$lnTO_{it}$	−0.53	−1.13	−2.66***	−3.24***

***Significance at the 1% level

*Significance at the 10% level

The numbers in parentheses indicate the probability values

Table 7 ARDL-PMG estimation results

Variables	Coefficient	*t*-Statistic	Probability
Long-run analysis			
$lnTOUR_{it}$	0.158*	1.696	0.094
FDI_{it}	0.001***	3.053	0.003
$lnGDP_{it}$	−0.657***	−3.823	0.000
$lnREC_{it}$	−0.054	−0.795	0.429
$lnTO_{it}$	−0.401***	−5.384	0.000
Constant	0.823	1.156	0.251
Short-run analysis			
$\Delta lnTOUR_{it}$	−0.071***	−2.995	0.003
ΔFDI_{it}	−0.001	−4.430	0.668
$\Delta lnGDP_{it}$	1.272***	3.531	0.000
$\Delta lnREC_{it}$	−0.405**	−2.279	0.025
$\Delta lnTO_{it}$	0.045	1.182	0.241
ECT_{t-1}	−0.228**	−2.247	0.032

***Significance at the 1% level

*Significance at the 1% and 5% level

in GDP increases environmental degradation by 1.27%, while in the long run, it decreases by 0.65%. Given the lower long-run income elasticity than in the short run, the EKC hypothesis holds true, indicating that the six ASEAN nations can improve their environmental quality through greater income.

The panel ARDL-PMG estimator shows that the FDI has an increasing effect on environmental degradation in the long run. In this case, the PHH hypothesis is valid and ASEAN countries are becoming the pollution havens of developed countries. Trade openness reduces CO_2 emissions in the long run. A 1% increase in trade openness reduces pollution by 0.40%. Tourism reduces CO_2 emissions in the short term, but increases them in the long run. A 1% increase in tourist arrivals raises pollution by 0.15%. In the short term, there is an inverse relationship between REC and CO_2 emissions. However, in the long term, this relationship does not exist.

Panel causality test results

Finally, we perform the DH panel causality test and report the relevant results in Table 8.

We observed bidirectional causality between CO_2 and GDP and between FDI and GDP. The causal relationships between these variables further strengthen the validity of the PHH and EKC hypothesis. Moreover, the lack of causality from REC to CO_2 confirms that renewable resources are underutilized. Since there is unidirectional causality from GDP to REC, the use of REC in ASEAN countries may increase in the future growth phase.

Discussion

The study analyzes EKC and PHH with a different approach for ASEAN countries. The analysis results show the validity of the EKC hypothesis. Unlike Saboori and Sulaiman (2013), Kisswani et al. (2019), and Vo et al. (2019), the finding that the EKC hypothesis is valid for ASEAN supports the outcomes of Heidari et al. (2015), Salman et al. (2019), Guzel and Okumus (2020), Kongbuamai et al. (2020), and Munir et al. (2020). The validity of the EKC hypothesis implies that environmental degradation that increases in the short run can be compensated by income growth in the long run. For this reason, it can be said that ASEAN countries can experience growth that ensures long-term environmental sustainability in addition to economic expansion.

The validity of PHH is consistent with the results of Guzel and Okumus (2020), in contrast to Chandran and Tang (2013). PHH states that developing countries apply lax environmental laws to attract foreign investment. ASEAN countries adopt such a strategy to attract more FDI, which increases environmental degradation. Therefore, the ASEAN region should direct FDI inflows to environmentally friendly investments. As Guzel and Okumus (2020) stated, although FDI supports the economic growth of ASEAN countries, dirty investment should be prevented by legal regulations.

The eco-friendly finding on trade openness is inconsistent with the Adeel-Farooq et al. (2021) study for ASEAN countries. This can be done through the technique effect, which enables foreign trade to support technological and environmental developments. The increase in income can lead to the import of more environmentally friendly technologies (Shahbaz et al. 2013). In addition, trade openness contributes to the development of the natural resources market, releasing green innovations and technologies that limit man-made emissions (Destek et al. 2021). The finding that trade openness reduces pollution is consistent with the results of Shahbaz et al. (2013), Destek and Sinha (2020), and Destek et al. (2021).

Tourism, on the other hand, increases environmental degradation in ASEAN countries. This finding supports the results of Solarin (2014), Andlib and Salcedo-Castro (2021), Selvanathan et al. (2021), Bin Amin and Aftabi Atique (2021), and Muhammad et al. (2021). ASEAN countries should use their revenues from tourist flows for more environmentally friendly purposes and promote green tourism. Governments should monitor the environmental degradation caused by tourists, and the damage to the ecosystem should be eliminated through environmental protection measures.

Contrary to expectations, renewable energy has no impact on CO_2 emissions, implying that ASEAN countries are not using renewable resources effectively and appropriately. Despite the abundant renewable resources in some of the ASEAN countries, these resources are consumed with low efficiency and some clean energy projects cannot be funded (Liu et al. 2017). Singapore, which has an area of 728.6 km^2, has almost no renewable resources. The other five ASEAN countries, on the other hand, focus on fossil fuel consumption and reduce the share of renewable energy in their total energy demand (see Fig. 2.). Our results are in line with the findings of Lin and Moubarak (2014), Al-Mulali et al. (2015), Pata (2018), and Pata and Caglar (2021), who confirm the long-term ineffectiveness of renewable energy for environmental quality.

Table 8 Causality results

No	H_0	W-Stat	Zbar-Stat	Probability	Causality
1	TOUR≠CO_2	519.353	118.522	0.2359	None
2	CO_2≠TOUR	433.035	0.58112	0.5612	None
3	FDI≠CO_2	421.465	0.50015	0.6170	None
4	CO_2≠FDI	874.542	367.103	0.0002***	CO_2→FDI
5	GDP≠CO_2	688.108	236.627	0.0180**	GDP→CO_2
6	CO_2≠GDP	153.212	827.314	0.000***	CO_2→GDP
7	REC≠CO_2	505.510	108.835	0.2764	None
8	CO_2≠REC	447.763	0.68420	0.4939	None
9	TO≠ CO_2	891.662	379.085	0.0002***	TO→CO_2
10	CO_2≠TO	857.199	354.965	0.0004***	CO_2→TO
11	FDI≠TOUR	432.400	0.57668	0.5642	None
12	TOUR≠FDI	804.812	318.302	0.0015***	TOUR→FDI
13	GDP≠TOUR	759.424	286.537	0.0042***	GDP→TOUR
14	TOUR≠GDP	411.156	0.42800	0.6687	None
15	REC≠TOUR	498.018	103.591	0.3002	None
16	TOUR≠REC	461.426	0.77982	0.4355	None
17	TO≠TOUR	282.941	−0.46932	0.6388	None
18	TOUR≠TO	865.153	360.532	0.0003***	TOUR→TO
19	GDP≠FDI	815.620	325.866	0.0011***	GDP→FDI
20	FDI≠GDP	652.209	211.502	0.0344**	FDI→GDP
21	REC≠FDI	472.210	0.85529	0.3924	None
22	FDI≠REC	427.403	0.54171	0.5880	None
23	TO≠FDI	592.435	169.669	0.0898*	TO→FDI
24	FDI≠TO	290.362	−0.41738	0.6764	None
25	REC≠GDP	457.195	0.75021	0.4531	None
26	GDP≠REC	591.558	169.056	0.0909*	GDP→REC
27	TO≠GDP	541.369	133.931	0.1805	None
28	GDP≠TO	947.992	418.507	0.000***	GDP→TO
29	TO≠REC	456.758	0.74715	0.4550	None
30	REC≠TO	442.550	0.64772	0.5172	None

***$p < 0.01$ represents statistical rejection level at 1%

**$p < 0.05$ represents statistical rejection level at 5%

*$p < 0.1$ represents statistical rejection level at 10%

The symbol "≠" denotes the null hypothesis of non-causality

Policy recommendations

Based on the findings, the study offers important policy implications for ASEAN countries to minimize the increase in CO_2 emissions. In order to increase environmental quality, ASEAN countries must first reduce their high dependence on fossil fuels. For this, fossil fuels and renewable resources can be substituted. However, renewable energy sources are not effectively utilized in ASEAN countries. Instead of focusing on renewable energy, a more accurate strategy could be to support income growth and steer society toward environmentally friendly goods and services that have access to high-income levels. As individual and societal incomes increase, so do people's health concerns and desire for a better quality of life. Thus, ASEAN societies may demand environmental improvement to have better air conditions and avoid climate risks. Since the EKC hypothesis is valid, the increase in income will become an environmentally friendly factor. Therefore, ASEAN governments must focus on policies that simultaneously implement economic and environmental development.

In addition, ASEAN governments should regulate the tourism sector. Tourism in its current structure increases environmental pollution in ASEAN countries. To reduce it, the ecotourism strategy could be a policy option. ASEAN governments can also adopt green tourism practices by following the United Nations sustainable tourism strategies to reduce the environmental damage caused by the tourism sector. In addition, CO_2 emissions can be reduced through clean transportation and clean zones for the tourism sector. Another strategy is to prevent pollution as much as possible by effectively recycling the waste generated by tourists.

Moreover, under trade liberalization, ASEAN countries can minimize their CO_2 emissions by opening up more, thereby importing green technologies. In this context, ASEAN countries should support foreign trade policies that provide technologies that promote green innovation and clean energy practices.

Of the six ASEAN countries studied, Singapore is one of the Asian Tigers. In recent years, Singapore has successfully achieved its goals of economic growth, sustainable development, and high living standards. During the 24-year analysis period, Singapore grew at an average rate of 5.37% (World Bank 2022). In parallel with this tremendous growth, Singapore has managed to reduce its CO_2 emissions through effective environmental policies (Zambrano-Monserrate et al. 2018b), and Fig. 1 shows that Singapore is the only country among the six ASEAN countries that can reduce its CO_2 emissions. Singapore has implemented the Environmental Pollution Control Act of 1999 for environmental purposes and has committed in the Paris Agreement of 2015 to reduce its CO_2 emissions by 36% from 2005 levels by 2030. Policymakers in other ASEAN countries can contribute to the environmental development of the ASEAN region by taking cues from Singapore's successes in preventing environmental degradation and analyzing the applicability of these measures in their own countries in terms of business and foreign trade.

Conclusions

Global warming and proposed solutions for contributing countries are widely discussed today. In this context, the determinants of pollution in countries whose CO_2 emissions continue to increase are analyzed with empirical studies and researchers develop various strategies for decarbonization. As one of the empirical attempts, this study aims to analyze various factors affecting CO_2 emissions for six ASEAN countries under the PHH and EKC hypothesis. For this purpose, we use the panel ARDL-PMG method and DH panel causality tests. Our empirical results indicate that the PHH and EKC hypotheses are valid for ASEAN countries. Moreover, the results of the study show that trade openness is effective in reducing CO_2 emissions, while the effect of renewable energy is limited in the short term. The tourism sector significantly increases environmental degradation in the long term. In addition, despite the validity of PHH, the long-term coefficient of FDI is extremely low, so it can be said that FDI is not an important determinant of CO_2 emissions. Singapore and Indonesia have significant FDI inflows, but these investments are generally in the service sector and their impact on CO_2 emissions is limited. The results of the causality tests confirm the findings of the panel ARDL-PMG. Overall, these findings show that economic growth and foreign trade are effective and useful environmental policy tools for ASEAN countries.

The present study has a number of limitations. First, only six countries were analyzed because data were not available for several ASEAN countries. Another limitation is that due to the methodology used, only panel results are presented and individual country results are not considered. Therefore, the study provides opportunities for future research. Future research could analyze more ASEAN countries using panel data methods with country-specific results. In addition, CO_2 emissions do not reflect water and soil pollution. Therefore, a stronger environmental assessment can be made if future research examines much broader environmental indicators such as ecological footprint and load capacity factor in ASEAN countries.

Author contribution **UKP**: supervision, conceptualization, software; **MMD**: writing – original draft, formal analysis, methodology, visualization; **FK**: data curation, writing – original draft, writing – review and editing.

Data availability The sources of data have been duly mentioned in the study.

Declarations

Ethics approval This article does not contain any studies with human participants performed by any of the authors.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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