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Economic Growth, Energy Consumption, and Environmental Sustainability in Southeast Asia: Evidence from Symmetric and Asymmetric Models

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Abstract

This study examines the effects of economic growth and energy consumption on environmental degradation in nine Southeast Asian countries from 1990 to 2022. By jointly employing carbon dioxide (CO_2) emissions and the ecological footprint (EFP) within both symmetric and asymmetric panel ARDL frameworks, the study provides a more comprehensive assessment of environmental sustainability than previous studies that rely on a single environmental indicator or a linear specification. The empirical results indicate that economic growth and energy consumption remain key drivers of environmental degradation, although their effects vary with the environmental indicator used. Both the panel ARDL and NARDL estimates support the EKC hypothesis when environmental degradation is measured by CO_2 emissions, but reject it when the EFP is used, highlighting the importance of adopting multidimensional measures of environmental sustainability. Furthermore, the panel NARDL results reveal significant long-run asymmetric effects of energy consumption, with increases in energy use exerting stronger adverse impacts on both CO_2 emissions and the EFP than equivalent decreases. These contrasting findings suggest that improvements in carbon efficiency associated with economic growth do not necessarily alleviate broader pressures on natural resources and ecological systems. The robustness of the results is confirmed using FMOLS, DOLS, and CCR estimators, while the causality analysis identifies long-run bidirectional relationships among economic growth, energy consumption, and environmental degradation. These findings emphasize the need for integrated policy measures that promote renewable energy adoption, cleaner industrial development, improved energy efficiency, and stronger environmental governance to support sustainable economic growth and accelerate the transition toward net-zero emissions in Southeast Asia.

Keywords: environmental sustainability; economic growth; energy consumption; panel ARDL; nonlinear ARDL

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1. Introduction

Over the past few decades, the environment has been increasingly exposed to numerous environmental concerns, including climate change, global warming, resource depletion, ecological distortion, and other environmental-related problems [1–6]. With the increasing demand for energy driven by rapid population growth, urbanization, and the expansion of the manufacturing and transportation sectors, individuals are forced to live in polluted, toxic environments [7,8]. According to the International Energy Agency (IEA) report published in 2022, carbon dioxide (CO_2) emissions account for more than 78% of total greenhouse gas emissions, with anthropogenic activities representing the dominant source. Previous studies consistently identify economic growth and energy consumption as the principal drivers of CO_2 emissions, while foreign direct investment, trade openness, population density, urbanization, and industrialization further influence environmental quality [4,5,9–12]. Moreover, sustained economic expansion in recent decades has been accompanied by rapidly increasing energy consumption, a trend expected to continue in the foreseeable future [13–21].

Achieving the United Nations Sustainable Development Goals (SDGs) by 2030 requires substantial reductions in greenhouse gas emissions, particularly in developing regions where economic growth remains highly dependent on fossil fuels. Southeast Asia is one of the world's fastest-growing economic regions and has become an important manufacturing and industrial hub. However, this rapid development has also intensified environmental and energy-related challenges. According to the 2023 IEA report, approximately 85% of the region's population is exposed to air pollution levels exceeding the World Health Organization's recommended safety thresholds. Since 2000, the region's energy demand has more than doubled, with most of the increase supplied by fossil fuels. Coal has experienced the largest expansion, increasing its share of the regional energy mix from 9% in 2000 to approximately 28% in recent years. Indonesia accounts for nearly 90% of Southeast Asia's coal production and is one of the world's leading exporters, while Vietnam is the region's second-largest producer and consumer.

The recent global energy crisis has further exposed the vulnerabilities of Southeast Asia's energy system. The region continues to rely heavily on imported fossil fuels, particularly oil, increasing exposure to volatile international energy prices and placing considerable pressure on government budgets and low-income households. Unlike many regions where economic growth has gradually become less carbon-intensive, Southeast Asia continues to exhibit a strong positive association between economic growth and carbon emissions. This pattern is primarily attributed to the increasing dependence on coal for electricity generation and industrial production, resulting in persistent growth in energy-related emissions.

According to the 2024 IEA report, Southeast Asia's future energy demand will continue to grow due to robust economic growth, rapid population growth, and the region's strategic role in global manufacturing. Without significant policy intervention, energy-related CO_2 emissions are projected to increase by approximately 33% by 2050, raising serious concerns regarding environmental sustainability, energy security, and dependence on imported fossil fuels. In response, nearly all Southeast Asian countries have adopted ambitious energy transition strategies, with eight of the ten ASEAN member states committing to achieve net-zero emissions by 2050. These developments underscore the urgent need to understand how economic growth and energy consumption affect environmental sustainability, and whether recent energy market disruptions will accelerate the transition toward cleaner, more sustainable energy systems.

Despite the growing body of literature on the energy–growth–environment nexus, several important research gaps remain. First, most studies of Southeast Asian countries rely exclusively on CO_2 emissions as a proxy for environmental degradation, potentially overlooking broader dimensions of environmental sustainability. Second, the literature predominantly employs linear econometric models that implicitly assume symmetric responses of environmental quality to changes in energy consumption. This assumption may be overly restrictive because macroeconomic variables frequently exhibit nonlinear behavior, implying that increases and decreases in energy consumption may produce different environmental outcomes. Third, relatively few studies simultaneously account for the roles of foreign direct investment, trade openness, population density, and industrialization within a unified empirical framework, despite their relevance to the SDGs. Consequently, whether linear models adequately capture the dynamics of the energy–environment relationship in Southeast Asia remains an open empirical question.

To address these research gaps, this study investigates the relationships among economic growth, energy consumption, and environmental sustainability in Southeast Asian countries, using annual data from 1990 to 2022. Specifically, the study pursues three main objectives. First, it examines long-run and short-run relationships among economic growth, energy consumption, and environmental sustainability using two complementary indicators of environmental degradation: carbon dioxide (CO_2) emissions and the ecological footprint (EFP). Second, it evaluates the effects of foreign direct investment, trade openness, population density, and industrialization on the growth–environment nexus. Third, it compares results from symmetric and asymmetric panel autoregressive distributed lag (ARDL) models to determine whether positive and negative changes in energy consumption have asymmetric effects on environmental degradation.

Accordingly, this study seeks to answer the following research questions: (1) What are the long-run and short-run effects of economic growth and energy consumption on environmental sustainability in Southeast Asia? (2) Do foreign direct investment, trade openness, population density, and industrialization significantly affect environmental degradation? (3) Do increases and decreases in energy consumption have asymmetric effects on CO_2 emissions and the ecological footprint?

The main contribution of this study extends beyond the application of both symmetric and asymmetric panel ARDL models [22]. Unlike previous studies that typically rely on either a single environmental indicator or a symmetric estimation framework, this study simultaneously employs CO_2 emissions and the ecological footprint as complementary measures of environmental degradation and compares linear and nonlinear dynamic specifications. This integrated framework enables assessment of whether conventional symmetric models obscure important nonlinear adjustment mechanisms and whether policy conclusions vary with the environmental indicator used. By capturing both the direction and magnitude of asymmetric responses, the study provides more robust evidence on the energy–environment nexus and offers richer policy implications for Southeast Asian economies pursuing low-carbon development, energy security, and net-zero emission targets.

The remainder of this paper is organized as follows. Section 2 reviews the relevant theoretical and empirical literature, with particular emphasis on studies focusing on Asian countries. Section 3 describes the data, variables, and econometric methodology. Section 4 presents and discusses the empirical findings. Finally, Section 5 concludes the study and provides policy implications.

2. Literature Review

While the Environmental Kuznets Curve (EKC) hypothesis posits that environmental degradation initially rises with economic growth before declining after a certain income threshold, the shape of this relationship may vary by the environmental indicator used [18,19,23–26]. Although CO_2 emissions and the ecological footprint (EFP) are both widely used proxies for environmental sustainability, they capture different dimensions of environmental pressure [10,15,20,21,27,28]. CO_2 emissions primarily measure greenhouse gas emissions from fossil fuel combustion and industrial activities, whereas the EFP reflects the broader demand placed on natural ecosystems by quantifying the biologically productive land and water required to support human consumption and absorb waste.

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Consequently, economic growth may influence these indicators through different transmission mechanisms. For instance, improvements in energy efficiency, technological innovation, and cleaner production processes can reduce carbon emissions without necessarily lowering overall resource consumption. Conversely, rising income may stimulate material consumption, land-use expansion, and natural resource exploitation, thereby increasing the EFP even when carbon emissions stabilize or decline. These conceptual differences provide a theoretical basis for expecting distinct EKC patterns for CO_2 emissions and the EFP, thereby justifying the inclusion of both indicators in empirical analyses of environmental sustainability.

Building on this conceptual distinction, the following section reviews the empirical literature on the relationships among economic growth, energy consumption, and environmental sustainability, with particular emphasis on evidence from Southeast Asian economies.

2.1. Economic Growth, Energy Consumption, and Environmental Sustainability

The relationship between economic growth and environmental sustainability has been widely examined through the EKC hypothesis. In Southeast Asia, Shahbaz et al. [24] found an N-shaped relationship between economic growth and CO_2 emissions in Vietnam during 1974–2016, indicating that environmental quality may improve temporarily before deteriorating again as income continues to rise. At the broader regional level, Munir and Ameer [19] reported an inverted U-shaped relationship between economic growth and SO_2 emissions across 11 Asian countries, supporting the EKC hypothesis. Similar evidence has been documented by Kongbuamai et al. [15] and Lu [28], who showed that although economic expansion initially intensifies environmental pressure, improvements in technology and production efficiency may partially offset these adverse effects in Asian economies.

Despite this evidence, the validity of the EKC remains controversial. Several studies have found that sustained economic growth continues to worsen environmental quality rather than improve it. Ahmed and Wang [3], Gulistan et al. [14], Alam et al. [18], Hassan et al. [20], and Murshed et al. [21] reported that economic expansion remains positively associated with environmental degradation, particularly in emerging Asian economies. These findings suggest that rising income alone is insufficient to improve environmental quality without complementary policies promoting clean energy, technological innovation, and sustainable resource management.

Energy consumption has consistently been identified as a major driver of environmental degradation in Asia. Munir and Riaz [4] demonstrated that fossil fuel consumption, including oil, natural gas, coal, and electricity, significantly increases CO_2 emissions in Bangladesh, India, and Pakistan. Similarly, Rehman and Rehman [11] showed that economic growth and energy consumption jointly contribute to environmental degradation across major Asian economies. Raihan et al. [16] reached similar conclusions for Bangladesh. Collectively, these studies indicate that the environmental consequences of rapid economic development in Southeast Asia are largely driven by rising energy demand and continued reliance on fossil fuels.

Although the existing literature has extensively examined the relationships among economic growth, energy consumption, and environmental degradation, most studies focus on either CO_2 emissions or the ecological footprint independently [29–40]. Few studies compare these two environmental indicators within a unified analytical framework, particularly in the context of Southeast Asia. Given their distinct environmental dimensions, examining whether economic growth generates different EKC patterns for CO_2 emissions and the ecological footprint can provide a more comprehensive understanding of environmental sustainability. Accordingly, this study extends the existing literature by examining whether

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economic growth exhibits different EKC patterns when environmental sustainability is measured using CO_2 emissions and the ecological footprint. By considering both indicators simultaneously, the study provides a more comprehensive assessment of environmental sustainability in Southeast Asia.

Grounded in the EKC hypothesis and the broader energy–environment literature, this study tests the following hypotheses:

H1. *Economic growth significantly influences environmental degradation in Southeast Asian countries.*

H2. *Energy consumption significantly increases environmental degradation.*

H3. *Positive and negative changes in energy consumption exert asymmetric effects on environmental degradation.*

2.2. FDI, Trade Openness, and Environmental Sustainability

Foreign direct investment (FDI) and trade openness are among the most widely studied determinants of environmental sustainability because of their significant roles in promoting economic integration and growth. However, the environmental consequences of these factors remain a subject of considerable debate. According to the pollution haven hypothesis (PHH), increased international investment and trade may lead pollution-intensive industries to relocate to countries with relatively weak environmental regulations, thereby exacerbating environmental degradation. Conversely, the PHH suggests that FDI and trade can improve environmental quality by transferring cleaner technologies, advanced managerial practices, and environmentally friendly production processes.

A substantial body of empirical literature supports the view that FDI contributes to environmental degradation. Perkins and Neumayer [41], using panel data for 77 countries from 1982 to 2005, found that FDI significantly increases CO_2 emissions. Similarly, Behera and Dash [42] reported that both FDI and energy consumption intensify CO_2 emissions in South and Southeast Asian economies. In India, Zameer et al. [43] found that FDI adversely affects environmental quality in the long run. For Pakistan, Munir and Ameer [44] demonstrated that positive FDI shocks significantly increase CO_2 emissions, while Khan et al. [39] found that both positive and negative FDI shocks contribute to environmental deterioration. Comparable evidence was reported by Tancho et al. [45] for Thailand, where both positive and negative FDI shocks were found to increase environmental degradation. At a broader level, Wei et al. [46] concluded that FDI negatively affects environmental sustainability in countries participating in the Belt and Road Initiative (BRI). Likewise, Udeagha and Ngepah [35], Derindag et al. [47], and Pata et al. [48] found that FDI increases CO_2 emissions in India and ASEAN-6 countries, respectively. These findings suggest that FDI often stimulates industrial activity and energy consumption, thereby increasing environmental pressures.

Trade openness has also been identified as a significant determinant of environmental quality, although empirical evidence remains mixed. Bernard and Mandal [49] examined 60 emerging and developing economies (including Southeast Asian countries) from 2002 to 2012 and found that trade openness improves the environmental performance index (EPI) while increasing CO_2 emissions. Similarly, Ertugrul et al. [50] showed that trade openness plays a significant role in increasing carbon emissions among the world's top ten CO_2 emitters, including Indonesia, Malaysia, and Thailand. In newly industrialized countries, including Indonesia, Malaysia, the Philippines, and Thailand, Zhang et al. [13] found that trade openness significantly influences environmental degradation through higher CO_2 emissions. Comparable results were reported by Munir and Ameer [19] for 11 Asian countries, where trade openness was found to increase long-run pollution levels.

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Furthermore, studies by Gulistan et al. [14], Kongbuamai et al. [15], Cetin et al. [29], Pata [31], Udeagha and Ngepah [35], Khan et al. [39], and Ling et al. [51] consistently reported that greater trade openness deteriorates environmental quality by increasing various forms of pollution. However, Derindag et al. [47] identified heterogeneous effects of trade openness, demonstrating that trade expansion increases emissions in low-carbon-intensity sectors while partially mitigating emissions in highly polluting Indian industries.

Overall, the existing literature suggests that both FDI and trade openness have significant effects on environmental sustainability. However, the direction and magnitude of these effects may vary across countries and sectors. Nevertheless, the preponderance of empirical evidence supports the view that increased foreign investment and trade integration tend to intensify environmental pressures through higher production, energy consumption, and emissions. Therefore, this study tests the following hypothesis.

H4. *FDI and trade openness significantly influence the relationship between economic growth and environmental degradation.*

2.3. Population, Industrialization, and Environmental Sustainability

Population growth and industrialization are widely recognized as key drivers of environmental sustainability. However, the empirical evidence regarding the impact of population growth on environmental quality remains inconclusive. A substantial body of literature argues that population growth exacerbates environmental degradation by increasing energy demand, resource consumption, and pollutant emissions. For example, Wang et al. [1], Alam et al. [18], Cole and Neumayer [52], Poumanyvong and Kaneko [53], Martínez-Zarzoso and Maruotti [54], Wang et al. [55], Zhang et al. [56], Sheng et al. [57], and Li et al. [58] show that population growth intensifies environmental pressures through higher energy consumption and greenhouse gas emissions. In contrast, Bekhet and Othman [2], Chen et al. [59], Charfeddine and Mrabet [60], and Danish et al. [61] argue that population growth can improve environmental sustainability by fostering technological innovation, generating economies of scale, and promoting more efficient resource utilization.

Evidence from Asia largely supports the environmental degradation hypothesis. Wang et al. [62] examined ASEAN-8 countries over the period 1980–2009 and identified both short- and long-run causal relationships between population growth and CO_2 emissions, concluding that demographic expansion is a major driver of environmental deterioration. Similarly, Ali et al. [63] found that population density significantly increases CO_2 emissions in South Asian countries. Nathaniel and Khan [64] reported that population growth enlarges the ecological footprint across six ASEAN countries—Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. Comparable findings were reported for Indonesia by Nathaniel [65] and Wafiq and Suryanto [66], while Ahmed et al. [67] demonstrated that population growth increases China's ecological footprint, thereby undermining environmental sustainability. In contrast, Kongbuamai et al. [15] found that population growth reduces Thailand's ecological footprint, suggesting that demographic expansion may, under certain conditions, contribute positively to environmental sustainability.

Alongside population growth, industrialization has also been identified as a critical determinant of environmental quality. The conventional view holds that industrial expansion increases energy consumption and pollutant emissions, thereby exacerbating environmental degradation. For example, Mahmood et al. [6] and Samargandi [68] found that industrialization significantly increased CO_2 emissions in Saudi Arabia. Similar conclusions were reported by Pata [7] for Turkey, and Munir and Ameer [44] and Ullah et al. [69] for Pakistan, all of whom concluded that industrialization contributes to higher carbon emissions and environmental degradation. Likewise, Okere et al. [70] found that industrialization adversely affects environmental sustainability in Argentina. Consistent with these findings, Udeagha and Ngepah [35] and Azam et al. [71] concluded that industrial development accelerates environmental degradation through increased energy consumption and emissions.

Overall, although the empirical literature presents some conflicting evidence, the predominant view is that population growth and industrialization intensify environmental pressures by increasing resource consumption, energy demand, and pollutant emissions. Given the rapid demographic expansion and industrial development observed in Southeast Asian economies, this study proposes the following hypothesis:

H5. *Population density and industrialization significantly affect the relationship between economic growth and environmental degradation.*

3. Materials and Methods

3.1. Model Specification

This study follows Aydin [12], Alam et al. [18], Shahbaz et al. [24], Mujtaba et al. [33], Alshehry and Belloumi [36], and Pata et al. [48] in analyzing the effects of economic growth and energy consumption on CO_2 emissions under the EKC hypothesis. The dependent variables are GDP per capita (GDPpc), GDPpc squared ($GDPpc^2$), and energy consumption; these are included as determinants of CO_2 emissions. Control variables include population density, foreign direct investment, trade openness, and industrialization. Therefore, the model is specified as follows:

$$CO_2 = f(GDPpc, GDPpc^2, EC, POP, FDI, TO, IND) \quad (1)$$

where CO_2, $GDPpc$, $GDPpc^2$, EC, POP, FDI, TO, and IND represent carbon dioxide emissions, GDP per capita, GDP per capita squared, energy consumption, population density, foreign direct investment inflows, trade openness, and industrialization, respectively.

As stated in the introduction, some scholars argue that CO_2 emissions are not a comprehensive indicator of environmental deterioration. For example, Baz et al. [10], Lu [38], Danish et al. [61], Nathaniel [65], Destek [72], Al-Mulali et al. [73], Ulucak and Bilgili [74], and Dogan et al. [75] assert that the ecological footprint (EFP) is a more comprehensive metric that better reflects environmental degradation than CO_2 emissions. According to these researchers, we represent EFP as a function of the relevant variables as follows:

$$EFP = f(GDPpc, GDPpc^2, EC, POP, FDI, TO, IND) \quad (2)$$

Equations (1) and (2) are analyzed within the EKC framework. Including $GDPpc^2$ in both the CO_2 emissions and EPF functions aims to assess whether an inverted U-shaped relationship exists between economic growth and environmental degradation. According to the EKC hypothesis, rising economic growth increases energy consumption, which in turn causes environmental degradation. The hypothesis further assumes that higher energy consumption, population density, FDI, trade openness, and industrialization increase CO_2 emissions and EFP.

Following Destek [72], Mujtaba et al. [76], and Mohamed et al. [77], Equations (1) and (2) can be expressed in the following log-linear form:

$$lnCO_2/EFP_{it} = \beta_i + \beta_{i1} lnGDPpc_{it} + \beta_{i2} GDPpc^2_{it} + \beta_{i3} lnEC_{it} + \beta_{i4} lnPOP_{it} + \beta_{i5} lnFDI_{it} + \beta_{i6} lnTO_{it} + \beta_{i7} lnIND_{it} + \varepsilon_t \quad (3)$$

where $i = 1, 2, \ldots, N$ is the country indicator, and $t = 1, 2, \ldots, T$ is the period; ln is the natural logarithm, β_i represents the intercept, $\beta_{i1} - \beta_{i7}$ are the estimated coefficients of the variables, and ε_t is the error term.

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Consistent with the empirical literature and in light of the EKC hypothesis, we theoretically anticipated that the coefficients of CO_2 emissions and EFP, with respect to real GDPpc, EC, POP, FDI, TO, and IND would be positive (i.e., $\beta_1, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7 > 0$). However, if the EKC hypothesis is supported, the estimated coefficient on the square of real GDP per capita would be negative ($\beta_2 < 0$). Therefore, we propose that real GDPpc, EC, POP, FDI, TO, and IND contribute to environmental degradation by increasing CO_2 emissions and EFP. In contrast, the $GDPpc^2$ mitigates environmental degradation.

3.2. Data

This study focuses on nine Southeast Asian economies: Brunei Darussalam, Cambodia, Indonesia, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam. These countries were selected based on the availability of consistent annual data for all variables included in the analysis over the study period (1990–2022). Specifically, ecological footprint (EFP) data are available from the Global Footprint Network [78], while data on CO_2 emissions, real GDP per capita (GDPpc), energy consumption (EC), and the remaining control variables—population (POP), foreign direct investment (FDI), trade openness (TO), and industrialization (IND)—are obtained from the World Bank's World Development Indicators [79]. Laos was excluded from the sample because complete and consistent data for all variables, particularly EFP and other model specifications, were unavailable over the entire study period (1990–2022). Therefore, only countries with complete observations were retained to construct a balanced panel dataset. Definitions, measurements, and data sources are detailed in Table A1 (Appendix A).

3.3. Estimation Techniques

The choice of estimation technique depends on the time-series properties of the variables and the study's objectives. Consistent with the EKC framework, this study aims to estimate both the long-run equilibrium relationship and the short-run dynamics among economic growth, energy consumption, and environmental degradation. Accordingly, panel unit root and cointegration tests are first conducted to determine the variables' orders of integration and to verify the existence of a long-run equilibrium relationship. The results indicate that the variables are integrated of mixed orders, I(0) and I(1), with none integrated of order two, I(2). Under these conditions, the panel ARDL framework is appropriate because it accommodates variables with mixed integration orders while simultaneously estimating both long-run and short-run relationships.

The symmetric relationship among economic growth, energy consumption, and environmental degradation is initially examined using the linear panel ARDL model proposed by Pesaran et al. [80]. Compared with conventional cointegration techniques, the ARDL approach offers several advantages. First, it can be applied when the regressors are a mixture of I(0) and I(1) variables. Second, it estimates the long-run equilibrium relationship and the associated short-run adjustment dynamics within a unified error-correction framework. Third, by incorporating lagged dependent and explanatory variables, the model reduces potential endogeneity arising from omitted variables and reverse causality through dynamic adjustment.

However, the linear ARDL model imposes the restrictive assumption that positive and negative changes in the explanatory variables exert identical effects on environmental degradation. This assumption may be inappropriate because increases and decreases in energy consumption can affect environmental quality differently, particularly in economies that remain highly dependent on fossil fuels. To account for such nonlinearities, this study further employs the nonlinear panel (NARDL) model developed by Shin et al. [22]. The panel NARDL framework decomposes energy consumption into positive and negative partial-sum processes, thereby allowing separate estimation of the effects of increases and decreases in energy consumption on environmental degradation in both the short run and the long run. Long-run and short-run asymmetries are subsequently evaluated using the Wald test.

Model estimation is conducted using both the Pooled Mean Group (PMG) estimator proposed by Pesaran et al. [81] and the Mean Group (MG) estimator proposed by Pesaran and Smith [82]. The PMG estimator imposes homogeneity on the long-run coefficients while permitting heterogeneity in the short-run dynamics, intercepts, and error variances, whereas the MG estimator allows both long-run and short-run coefficients to vary across countries. The choice between these estimators is determined using the Hausman specification test [83]. Given that Southeast Asian countries may exhibit heterogeneous short-run adjustment processes while sharing similar long-run economic and environmental objectives, the PMG estimator is expected to provide more efficient estimates when the null hypothesis of long-run homogeneity cannot be rejected.

To assess the robustness of the estimated long-run coefficients, three alternative panel cointegration estimators are employed: Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR). FMOLS corrects for endogeneity and serial correlation through nonparametric adjustments to the error term. DOLS addresses endogeneity by augmenting the cointegrating regression with leads and lags of the first-differenced explanatory variables, thereby producing unbiased and efficient long-run estimates, particularly in finite samples. CCR eliminates endogeneity and serial correlation by transforming the variables before estimation. Consistent results across FMOLS, DOLS, and CCR would provide strong evidence of the robustness and reliability of the estimated long-run relationships.

The optimal lag structure for both the linear and nonlinear panel ARDL models is selected using the Akaike Information Criterion (AIC), which balances model fit and parsimony and has been shown to perform well in finite samples. Finally, a series of diagnostic and specification tests—including panel unit root and cointegration tests, the Hausman specification test, Wald symmetry tests, and robustness analyses using FMOLS, DOLS, and CCR—is conducted to assess the validity, stability, and reliability of the estimated models. All econometric analyses were performed using Stata version 17.0.

3.3.1. Linear Panel ARDL Model

Following Pesaran et al. [81], Equation (3) can be expressed in the linear panel ARDL model within the EKC framework as follows:

$$\begin{aligned}\Delta lnCO_2/EFP_{it} = \; & \beta_i + \beta_{1i} lnCO_{2i,t-1} + \beta_{2i} lnGDPpc_{i,t-1} + \beta_{3i} lnGDPpc^2_{i,t-1} + \beta_{4i} lnEC_{i,t-1} + \beta_{5i} lnPOP_{i,t-1} + \\ & \beta_{6i} lnFDI_{i,t-1} + \beta_{7i} lnTO_{i,t-1} + \beta_{8i} lnIND_{i,t-1} + \textstyle\sum_{j=1}^{p} \delta_{1ij} \Delta lnCO_2/EFP_{i,t-j} + \textstyle\sum_{j=0}^{q} \delta_{2ij} ln\Delta GDPpc_{i,t-j} + \\ & \textstyle\sum_{j=0}^{q} \delta_{3ij} \Delta lnGDPpc^2_{i,t-J} + \textstyle\sum_{j=0}^{q} \delta_{4ij} \Delta lnEC_{i,t-j} + \textstyle\sum_{j=0}^{q} \delta_{5ij} \Delta lnPOP_{i,t-j} + \textstyle\sum_{j=0}^{q} \delta_{6ij} \Delta lnFDI_{i,t-j} + \\ & \textstyle\sum_{j=0}^{q} \delta_{7ij} \Delta lnTO_{i,t-j} + \textstyle\sum_{j=0}^{q} \delta_{8ij} \Delta lnIND_{i,t-j} + \mu_i + \varepsilon_{it}\end{aligned} \quad (4)$$

where β_i denotes the constant term, while Δ represents the first difference operator, the parameters β_{ki} (k = 1, 2, 3, 4, 5, 6, 7, 8) denote the long-run coefficients. δ_{sij} (s = 1, 2, 3, 4, 5, 6, 7, 8) represent the short-run coefficients. p and q indicate the optimal lag lengths, which are determined using the Akaike Information Criterion (AIC), μ_i denotes the country-fixed effects, and ε_{it} is the error term.

Equation (4) can be reformulated into its error-correction representation by incorporating an error-correction term, as shown in Equation (5):

$$\Delta lnCO_2/EFP_{it} = \varphi_i + \sum_{j=1}^{p-1} \delta_{1ij} \Delta lnCO_2/EFP_{i,t-j} + \sum_{j=0}^{q} \delta_{2ij} ln\Delta GDP_{i,t-j} + \sum_{j=0}^{q} \delta_{3ij} \Delta lnGDP^2_{i,t-j} + \sum_{j=0}^{q} \delta_{4ij} \Delta lnEC_{i,t-j} + \sum_{j=0}^{q} \delta_{5ij} \Delta lnPOP_{i,t-j} + \sum_{j=0}^{q} \delta_{6ij} \Delta lnFDI_{i,t-j} + \sum_{j=0}^{q} \delta_{7ij} \Delta lnTO_{i,t-j} + \sum_{j=0}^{q} \delta_{8ij} \Delta lnIND_{i,t-j} + \lambda_i ECT_{i,t-1} + \mu_i + \varepsilon_{it} \quad (5)$$

where λ_i represents the speed-of-adjustment coefficient, indicating how quickly deviations from the long-term equilibrium are corrected after a short-term shock. The term $ECT_{i,t-1}$ refer to the lagged error-correction term, which is expected to be negative and statistically significant.

3.3.2. Nonlinear Panel ARDL Model

Equation (5) captures only symmetric relationships among GDPpc, GDPpc^2, EC, POP, FDI, TO, IND, and environmental degradation (i.e., CO_2 emissions and EFP), assuming a linear and symmetric long-run cointegrating relationship. Under this specification, positive and negative changes in EC are implicitly assumed to exert identical effects on environmental degradation. However, such an assumption may produce biased estimates and lead to misleading policy implications if the underlying relationships are asymmetric.

To overcome this limitation, this study employs the panel NARDL approach proposed by Shin et al. [22], which explicitly accounts for the asymmetric effects of EC. Specifically, the panel NARDL model decomposes EC into its positive and negative partial sums, as shown in Equation (6), enabling an assessment of whether increases and decreases in EC have different impacts on CO_2 emissions and EFP. Moreover, the model distinguishes between the short-run and long-run effects of the explanatory variables on environmental degradation, thereby providing a more comprehensive understanding of their dynamic relationships.

$$\begin{aligned} lnEC^+_{it} &= \sum_{j=1}^{t} \Delta lnEC^+_{i,j} = \sum_{j=1}^{t} \max(\Delta lnEC_{i,j}, 0) \\ lnEC^-_{it} &= \sum_{j=1}^{t} \Delta lnEC^-_{i,j} = \sum_{j=1}^{t} \min(\Delta lnEC_{i,j}, 0) \end{aligned} \quad (6)$$

where positive changes in the EC variable, $\Delta lnEC^+_{i,j}$ represent increases, whereas negative changes, $\Delta lnEC^-_{i,j}$ capture decreases. To account for potential asymmetric effects, Equation (5) is reformulated by incorporating the positive and negative partial sum decompositions of $lnEC$, as defined in Equation (6). Consequently, the asymmetric error correction model is specified in Equation (7) as follows:

$$\Delta lnCO_2/EFP_{it} = \psi_i + \sum_{j=1}^{p-1} \gamma_{1ij} \Delta lnCO_2/EFP_{i,t-j} + \sum_{j=0}^{q} (\theta^+_{1ij} \Delta lnEC^+_{i,t-j} + \theta^-_{1ij} \Delta lnEC^-_{i,t-j} + \theta_{2ij} \Delta lnGDP_{i,t-j} + \theta_{3ij} \Delta lnGDP^2_{i,t-j} + \theta_{4ij} \Delta lnPOP_{i,t-j} + \theta_{5ij} \Delta lnFDI_{i,t-j} + \theta_{6ij} \Delta lnTO_{i,t-j} + \theta_{7ij} \Delta lnIND_{i,t-j}) + \lambda_i ECT_{i,t-1} + \mu_i + \varepsilon_{it} \quad (7)$$

where λ_i represents the coefficient of the speed adjustment. $ECT_{i,t-1} = [\vartheta^+_{1i} lnEC^+_{i,t-1} + \vartheta^-_{1i} lnEC^-_{i,t-1} + \vartheta_{2i} lnGDP_{i,t-1} + \vartheta_{3i} lnGDP^2_{i,t-1} + \vartheta_{4i} lnFDI_{i,t-1} + \vartheta_{5i} lnTO_{i,t-1} + \vartheta_{6i} lnIND_{i,t-1}]$ is the nonlinear error correction term. The long-run asymmetric multipliers of EC can be calculated as $\vartheta^+ = \frac{\theta^+}{\rho_i}$ and $\vartheta^- = \frac{\theta^-}{\rho_i}$. If $\rho_i = 0$, it suggests that there is no long-run asymmetric association between EC and CO_2 emissions or EFP. Long-run and short-run symmetry is tested using the Wald test. The null hypothesis is stated as follows: $H_0 : \theta^+ = \theta^-$ against $H_1 : \theta^+ \neq \theta^-$, and rejecting the null hypothesis suggests that the EC exhibits an asymmetric impact on CO_2 emissions or EFP in the long run. Likewise, the null hypothesis of the short-run symmetric coefficient is stated as: $H_0 : \vartheta^+_{ij} = \vartheta^-_{ij}$ against $H_1 : \vartheta^+_{ij} \neq \vartheta^-_{ij}$ for all $j = 0, \ldots, p$, and rejecting the null hypothesis implies that EC shows an asymmetric impact on CO_2 emissions or EFP in the short run.

4. Results and Discussion

4.1. Descriptive Statistics

Table 1 presents descriptive statistics and pairwise correlations for all variables. The sample statistics show that the means of CO_2 emissions, EFP, GDPpc, EC, POP, FDI, TO, and IND are positive, indicating an upward trend. All variable means fall between the minimum and maximum values, confirming consistency. Except for CO_2 emissions and EFP, the standard deviation of each variable is less than its mean, suggesting stability throughout the sample period. Most variables are positively skewed, while only CO_2 emissions, TO, and IND are negatively skewed. The kurtosis indicates that CO_2 emissions, EFP, GDPpc, EC, and TO have heavy tails (leptokurtic), whereas POP, FDI, and IND have light tails (platykurtic). The Jarque–Bera statistic indicates that all variables are normally distributed.

Table 1. Descriptive statistics and pairwise correlations among variables.

	$\ln CO_2$	lnEFP	lnGDPpc	lnEC	lnPOP	lnFDI	lnTO	lnIND
Mean	0.6515	0.7212	8.2360	6.9363	5.2072	1.1902	4.3584	3.4774
Median	0.6774	0.4658	8.0491	6.6209	4.7563	1.1851	4.3969	3.5939
Maximum	3.0925	2.1219	11.1265	9.1743	8.9829	3.4538	5.8391	4.3056
Minimum	−3.1229	−0.5192	5.1092	5.4781	3.9060	−2.8701	3.1390	0.1094
Std. Dev.	1.5054	0.7406	1.4956	1.1563	1.3712	1.0789	0.6904	0.5776
Skewness	−0.3105	0.4430	0.2384	0.4832	1.8343	0.5431	−0.1742	−2.9391
Kurtosis	2.2651	1.8043	2.2484	1.8135	5.2029	4.1403	2.1316	3.4277
Jarque–Bera	11.4571	27.4069	9.8047	28.9837	231.4405	30.6915	10.8342	534.688
Probability	0.1513	0.1458	0.1842	0.1276	0.1346	0.1253	0.1334	0.1245
Obs.	297	297	297	297	297	297	297	297
$\ln CO_2$	1.0000	------						
lnEFP	------	1.0000						
lnGDPpc	0.9475 ***	0.9436 ***	1.0000					
lnEC	0.9280 ***	0.9560 ***	0.9518 ***	1.0000				
lnPOP	0.3455 ***	0.3918 ***	0.4940 ***	0.3485 ***	1.0000			
lnFDI	0.0738	0.2309 ***	0.1562 ***	0.1112 ***	0.4653 ***	1.0000		
lnTO	0.7469 ***	0.7423 ***	0.7224 ***	0.7026 ***	0.6094 ***	0.2974 ***	1.0000	
lnIND	−0.0297	−0.0042	0.0177	0.0378	−0.0856	−0.0522	−0.1964 ***	1.0000

Note: All variables are transformed into natural logarithms. *** denotes statistical significance at the 1% level.

The pairwise correlation analysis shows that all variables, except IND, are positively correlated with CO_2 emissions and EFP. Most importantly, GDPpc, EC, and TO are strongly associated with CO_2 emissions and EFP, while POP and FDI are only slightly correlated with CO_2 emissions and EFP. In addition, Figures A1 and A2 (Appendix B) show trends in CO_2 emissions (EFP), GDPpc, and EC for the full sample from 1990 to 2022. Both figures indicate that the three time series move almost in lockstep.

4.2. Cross-Sectional Dependence Test

To avoid biased estimates and conclusions, cross-sectional dependence (CD) is one of the most important diagnostics to consider before performing panel data analysis. Therefore, to test for serial dependence among the variables, we employed four CD tests: specifically, the Breusch–Pagan LM test [84], the Pesaran scaled LM test [85], the bias-corrected scaled LM test [86], and the Pesaran CD test. The null hypothesis for these tests is that "no cross-sectional dependence exists in the data." The results in Table 2 reject the null hypothesis at the 1% significance level across all tests and indicate cross-sectional dependence in the panel data models.

Table 2. Cross-sectional dependence test results.

Test	Breusch-Pagan LM		Pesaran Scaled LM		Bias-Corrected Scaled LM		Pesaran CD	
	Statistic	Prob.	Statistic	Prob.	Statistic	Prob.	Statistic	Prob.
$lnCO_2$	730.821 ***	(0.000)	81.885 ***	(0.000)	81.745 ***	(0.000)	17.416 ***	(0.000)
lnEFP	410.651 ***	(0.000)	44.153 ***	(0.000)	44.012 ***	(0.000)	17.611 ***	(0.000)
lnGDPpc	1046.326 ***	(0.000)	119.068 ***	(0.000)	118.927 ***	(0.000)	19.204 ***	(0.000)
$lnGDPpc^2$	1055.239 ***	(0.000)	120.118 ***	(0.000)	119.978 ***	(0.000)	19.224 ***	(0.000)
lnEC	349.524 ***	(0.000)	36.949 ***	(0.000)	36.808 ***	(0.000)	9.573 ***	(0.000)
lnPOP	1168.259 ***	(0.000)	133.438 ***	(0.000)	133.297 ***	(0.000)	34.179 ***	(0.000)
lnFDI	67.656 ***	(0.001)	3.731 ***	(0.000)	3.590 ***	(0.000)	1.362 ***	(0.001)
lnTO	188.568 ***	(0.000)	17.980 ***	(0.000)	17.839 ***	(0.000)	5.225 ***	(0.000)
lnIND	338.095 ***	(0.000)	35.602 ***	(0.000)	35.461 ***	(0.000)	5.129 ***	(0.000)

Note: Null hypothesis (H0): there is no cross-sectional dependence in the panel data. *** indicates rejection of the null hypothesis at the 1% significance level.

The CD test results suggest that second-generation panel unit root tests are more appropriate for assessing the variables' unit root properties and would yield more accurate results than first-generation tests.

4.3. Panel Unit Root Test

As documented in the literature, non-stationary data may produce erroneous regression results. In addition, checking for the presence of a unit root is important for determining the most appropriate method for data analysis. Thus, to assess the stationarity properties of the variables, the cross-sectionally augmented IPS (CIPS) panel unit root test proposed by Pesaran [87] is conducted to determine whether a unit root is present.

The CIPS test results in Table 3 show that all variables are non-stationary at the level and stationary at first difference, except for the EFP and FDI variables, which are integrated of order zero, i.e., I(0), with intercept and intercept-and-trend in the panel group. These results indicate that the data used in this study's models have different integration orders; that is, some variables are integrated of order zero [I(0)], while others are integrated of order one [I(1)]. Thus, we can conclude that all series might be cointegrated.

Table 3. Results of Pesaran's CIPS panel unit root test.

Variables	Level		First Difference		Conclusion
	Intercept	Intercept & Trend	Intercept	Intercept & Trend	
$lnCO_2$	−2.1387	−2.1839	−4.5787 ***	−4.5953 ***	I(1)
lnEFP	−2.8609 ***	−2.9795 **	--	--	I(0)
lnGDPpc	−1.6880	−1.8486	−3.1631 ***	−3.0939 **	I(1)
$lnGDPpc^2$	−2.0679	−2.7186	−2.9386 ***	−3.1778 ***	I(1)
lnEC	−2.3581	−2.6658	−3.8806 ***	−3.3126 ***	I(1)
lnPOP	−1.9493	−2.1537	−3.0670 ***	−2.4919	I(1)
lnFDI	−2.5785 ***	−3.8268 ***	--	--	I(0)
lnTO	−1.5088	−2.9932	−4.6167 ***	−4.8825 ***	I(1)
lnIND	−1.3446	−2.9387	−2.8298 ***	−3.0300 **	I(1)

Note: Null hypothesis (H0): the presence of a unit root with cross-sectional dependence in the time-series data. Individual lag lengths are selected using the AIC. ** and *** denote statistical significance at the 5% and 1% levels, respectively.

4.4. Panel Cointegration Test

After determining that the series are I(0) and I(1), we conducted panel cointegration tests to assess long-run relationships among the variables. To do so, we employed three panel cointegration tests proposed by Pedroni [88,89], Kao [90], and Westerlund [91]. Each test computes its statistics under different assumptions and methods. The null hypothesis for all these tests is that "there is no cointegration among the series." The results reported in Table 4 show that both the Pedroni and Kao panel cointegration tests reject the null hypothesis of no cointegration at the 1% significance level, indicating that the variables included in both models are cointegrated.

Table 4. Results of the Pedroni and Kao panel cointegration tests.

Pedroni Residual Cointegration Test						**Kao Residual Cointegration Test**		
Alternative Hypothesis: Common AR Coefficients (Within-Dimension)			**Alternative Hypothesis: Individual AR Coefficients (Between-Dimension)**					
Model 1: $lnCO_2 = f(lnGDPpc, lnGDPpc^2, lnEC, lnPOP, lnFDI, lnTO, lnIND)$								
	Statistic	Prob.		Statistic	Prob.		t-statistic	Prob.
Panel v-statistic	−0.956	(0.678)	Group rho-statistic	2.783	(0.996)	ADF	−2.997 **	(0.022)
Panel rho-statistic	2.133	(0.965)	Group PP-statistic	−5.985 ***	(0.000)			
Panel PP-statistic	−1.553 **	(0.042)	Group ADF-statistic	−4.740 ***	(0.000)			
Panel ADF-statistic	−1.564 **	(0.031)						
Model 2: $lnEFP = f(lnGDPpc, lnGDPpc^2, lnEC, lnPOP, lnFDI, lnTO, lnIND)$								
	Statistic	Prob.		Statistic	Prob.		t-statistic	Prob.
Panel v-statistic	−0.958	(0.833)	Group rho-statistic	2.785	(0.998)	ADF	−2.995 **	(0.021)
Panel rho-statistic	2.135	(0.954)	Group PP-statistic	−5.979 ***	(0.000)			
Panel PP-statistic	−1.549 ***	(0.000)	Group ADF-statistic	−4.742 ***	(0.000)			
Panel ADF-statistic	−1.562 ***	(0.000)						

Note: The null hypothesis (H0) for the Pedroni and Kao residual panel cointegration tests is that the series are not cointegrated. ** and *** indicate rejection of the null hypothesis at the 5% and 1% significance levels, respectively.

This finding is supported by the Westerlund cointegration test, as shown in Table A2 (Appendix A). Therefore, we conclude that a stable long-run equilibrium relationship exists. Consequently, the long-run panel ARDL estimation technique is appropriate for estimating the long-run coefficients.

4.5. Results of EKC Panel ARDL Estimates

As noted earlier, the PMG and MG estimators were compared using the Hausman specification test to determine whether the long-run slope coefficients were homogeneous across countries. The Hausman test results, reported in Table A3 (Appendix A), indicate that the null hypothesis of long-run homogeneity cannot be rejected for either model, as the corresponding p-values exceed the 5% significance level. Consequently, the PMG estimator is preferred because it provides more efficient and consistent estimates under the homogeneity assumption [92]. The long-run and short-run ARDL-PMG estimation results for the CO_2 emissions and EFP models are presented in Table 5.

Overall, the panel ARDL estimates reveal a stable long-run relationship among economic growth, energy consumption, and environmental degradation in Southeast Asian countries. Most explanatory variables are statistically significant in the long run, although their effects differ depending on whether environmental degradation is measured by CO_2 emissions or by the EFP. These contrasting results highlight the importance of considering multiple environmental indicators when evaluating the sustainability implications of economic development.

Table 5. Results of the EKC panel ARDL estimates.

	Dependent Variable: D(lnCO_2)			Dependent Variable: D(lnEFP)		
Variables	**Coefficient**	**t-Statistic**	**Prob.**	**Coefficient**	**t-Statistic**	**Prob.**
Long-run coefficients						
lnGDPpc	8.940 ***	8.867	0.000	−4.310 ***	−6.915	0.000
lnGDPpc^2	−0.435 ***	−7.571	0.000	0.304 ***	7.811	0.000
lnEC	0.231 **	2.103	0.036	−0.422 ***	−4.850	0.000
lnPOP	−1.042 ***	−11.468	0.000	−0.437 ***	−6.965	0.000
lnFDI	−0.013 *	−0.841	0.094	0.071 ***	6.928	0.000
lnTO	0.185 **	3.936	0.032	0.198 ***	6.387	0.000
lnIND	0.208 *	1.760	0.078	−0.101 *	−0.793	0.095
Trend	−0.005 ***	−1.667	0.000	−0.000 ***	−0.128	0.000
Short-run coefficients						
ECT(-1)	−0.273 ***	−2.415	0.001	−0.359 ***	−2.165	0.000
D(lnGDPpc)	−12.993	−0.833	0.405	−42.900	−0.851	0.396
D(lnGDPpc(-1))	16.350	1.539	0.125	−3.952	−0.671	0.502
D(lnGDPpc^2)	0.622	0.832	0.406	2.133	0.888	0.375
D(lnGDPpc^2(-1))	−0.897 *	−1.661	0.098	0.176	0.542	0.588
D(lnGDPpc^2(-2))	−0.012	−0.308	0.758	−−−	−−−	−−−
D(lnEC)	0.013	0.071	0.943	0.217 **	2.146	0.033
D(lnEC(-1))	0.076	0.659	0.510	0.119	0.735	0.463
D(lnEC(-2))	0.003	0.027	0.978	0.172 *	1.928	0.055
D(lnPOP)	17.860	1.385	0.167	4.665	0.596	0.551
D(lnPOP(-1))	−29.318 *	−1.845	0.066	−9.663	−0.678	0.498
D(lnPOP(-2))	25.062 *	1.733	0.084	−−−	−−−	−−−
D(lnFDI)	0.007	0.342	0.732	−0.000	−0.067	0.946
D(lnFDI(-1))	−0.019	−0.853	0.394	−0.014	−1.282	0.201
D(lnFDI(-2))	0.002	0.149	0.881	−0.002	−0.104	0.917
D(lnTO)	0.123	0.924	0.356	0.007	0.097	0.923
D(lnTO(-1))	0.081	0.857	0.392	−−−	−−−	−−−
D(lnTO(-2))	−0.021	−0.355	0.722	−−−	−−−	−−−
D(IND)	−0.702 ***	−2.701	0.007	−0.056	−0.302	0.763
D(IND(-1))	−0.105	−0.419	0.675	0.020	0.125	0.901
D(IND(-2))	0.196	0.831	0.406	−−−	−−−	−−−
Constant	−8.562 ***	−1.822	0.000	6.367 ***	2.354	0.000

Note: Model selection was conducted using the AIC. The optimal lag structures were PMG (1,2,3,3,3,3,3,3) for the CO_2 emissions model and PMG (1,2,2,3,2,3,1,2) for the EFP model. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

For the CO_2 emissions specification, the estimated coefficients of real GDPpc and its squared term are positive and negative, respectively, and both are statistically significant. This finding supports the EKC hypothesis by indicating an inverted U-shaped relationship between economic growth and carbon emissions. In the early stages of economic development, economic growth is accompanied by rising CO_2 emissions owing to increased industrial production, urbanization, and fossil fuel consumption. However, beyond a certain income threshold, further economic growth reduces carbon emissions, suggesting improvements in energy efficiency, technological progress, and environmental regulation. These findings are consistent with those reported by Alam et al. [18], Munir and Ameer [19], Murshed et al. [21], Cetin et al. [29], Afridi et al. [30], Waqih et al. [32], Mujtaba et al. [33], Balsalobre-Lorente et al. [34], Udeagha and Ngepah [35], Alshehry and Belloumi [36], Mohamed et al. [77], Zhu et al. [93], Rehman and Rashid [94], and Hao et al. [95], but contradicts Danish and Wang [5], Sarkodie and Strezov [26], Ali et al. [27], Ziyazov and Pyzhev [38], Mrabet and Alsamara [96], Aslam et al. [97], and Gogoi and Hussain [98].

In the short run, however, the estimated coefficients suggest a U-shaped relationship, implying that temporary fluctuations in economic activity do not immediately generate the long-run environmental improvements predicted by the EKC hypothesis.

EC exerts a positive and statistically significant effect on CO_2 emissions in the long run, indicating that continued dependence on fossil fuel-based energy remains an important source of environmental degradation in Southeast Asia. Specifically, a 1% increase in EC leads to approximately a 0.231% increase in CO_2 emissions. This result reflects the region's reliance on coal, oil, and natural gas to sustain rapid economic growth and industrial expansion. Consequently, improvements in environmental quality will require accelerating the transition toward renewable energy, improving energy efficiency, and adopting cleaner production technologies. POP exhibits a negative and statistically significant long-run relationship with CO_2 emissions. Although this finding differs from the conventional expectation that population growth increases environmental pressure, it may reflect the relatively lower energy intensity and more compact urban development patterns observed in several Southeast Asian countries. Similar evidence has been reported by Alshehry and Belloumi [36], Zhu et al. [93], and Rehman and Rashid [94], whereas Rehman and Rehman [11], Ali et al. [27], Mujtaba et al. [33], and Wang et al. [62] reported a positive relationship between population growth and environmental degradation.

The estimated coefficient on FDI is negative and statistically significant, suggesting that FDI contributes to improving environmental quality in the long run. This finding supports the technology transfer hypothesis, whereby foreign investment facilitates the diffusion of cleaner production techniques and environmentally friendly technologies. Moreover, the result is consistent with the Porter hypothesis, which argues that technological innovation stimulated by international investment can improve both environmental and economic performance. Similar findings have been reported by Waqih et al. [32], Alshehry and Belloumi [36], Zameer et al. [43], and Zhu et al. [93], although these studies differ from those supporting the pollution haven hypothesis [39,41,42,45–48,71,98–100].

TO has a positive and significant long-run effect on CO_2 emissions, implying that greater integration into international markets has increased environmental pressure by expanding energy-intensive production and export-oriented industries. Likewise, IND exerts a positive influence on CO_2 emissions, suggesting that the current pattern of industrial development in Southeast Asia remains heavily dependent on carbon-intensive production processes. These findings indicate that although trade liberalization and industrialization contribute to economic growth, they also increase environmental costs unless accompanied by cleaner technologies and stronger environmental regulations. Similar conclusions have been reached by Mahmood et al. [6], Pata [7], Udeagha and Ngepah [35], Zameer et al. [43], Ling et al. [51], Munir and Ameer [44], Gogoi and Hussain [98], and Shahbaz et al. [101].

The estimated ECT(−1) is negative and highly significant (−0.273), confirming the existence of a stable long-run equilibrium relationship among the variables. The coefficient indicates that approximately 27.3% of any short-run disequilibrium is corrected within one year, demonstrating a relatively moderate speed of adjustment toward the long-run equilibrium.

When environmental degradation is measured using the EFP, a different pattern emerges. Although the long-run relationship remains statistically significant, the estimated coefficients imply a U-shaped relationship between economic growth and environmental degradation, thereby rejecting the EKC hypothesis. Real GDPpc initially reduces the EFP, whereas its squared term becomes positive, indicating that beyond a certain income level, further economic growth increases ecological pressure. This result suggests that improvements in carbon efficiency associated with economic development do not necessarily reduce the broader environmental impacts arising from increased resource consumption, land use,

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and ecological demand. Consequently, economic growth alone is insufficient to ensure environmental sustainability when environmental quality is assessed using a multidimensional indicator such as the EFP. These findings are consistent with Rahman et al. [25], Mujtaba et al. [76], Destek and Sarkodie [102], Ansari et al. [103], Ansari et al. [104], Destek and Sinha [105], Dogan et al. [106], and Khan et al. [107], but differ from Ahmed and Wang [3], Kongbuamai et al. [15], Hassan et al. [20], Lu [38], Danish et al. [61], Nathaniel [65], Dogan et al. [75], Mujtaba et al. [76], Mohamed et al. [77], and Mrabet and Alsamara [96].

Interestingly, EC exhibits a negative long-run relationship with the EFP, suggesting that improvements in energy efficiency, structural transformation, and the gradual adoption of cleaner energy technologies may have reduced broader ecological pressures during the study period. Nevertheless, the coexistence of declining ecological footprints and rising CO_2 emissions suggests that the environmental consequences of EC vary across indicators, underscoring the importance of evaluating environmental sustainability using complementary measures rather than relying solely on carbon emissions.

POP also exerts a significant negative influence on the EFP, while FDI and TO are positively associated with ecological degradation. These findings suggest that increasing international investment and trade continue to expand production and resource use, thereby increasing ecological pressure despite their potential economic benefits. In contrast, IND has a negative long-run effect on the EFP, implying that technological upgrading and improvements in industrial efficiency have generated environmental benefits that outweigh the adverse effects of industrial expansion. This result supports the view that environmentally oriented industrial development can contribute to sustainable growth when accompanied by cleaner technologies and the adoption of renewable energy.

The short-run estimates broadly confirm the long-run findings. In particular, the U-shaped relationship between economic growth and the EFP persists, indicating that short-run economic expansion is likewise associated with increasing ecological pressure after a certain development threshold. The ECT(−1) is negative and statistically significant (−0.359), confirming the existence of a stable long-run equilibrium relationship and indicating that approximately 35.9% of short-run disequilibrium is corrected within one year.

Taken together, the panel ARDL results reveal that the validity of the EKC hypothesis depends critically on the environmental indicator employed. While CO_2 emissions suggest that economic growth may eventually improve environmental quality, the EFP indicates that broader ecological pressures continue to intensify as income increases. These contrasting findings underscore the importance of adopting multidimensional indicators for evaluating environmental sustainability and designing policies to achieve long-term green growth in Southeast Asia.

4.6. Results of EKC Panel NARDL Estimates

One of the primary objectives of this study is to determine whether the effects of energy consumption on environmental degradation are symmetric or asymmetric in Southeast Asian countries. To address this issue, a Wald symmetry test was performed. The results, reported in Table A4 (Appendix A), reject the null hypothesis of long-run symmetry for both CO_2 emissions and the EFP, indicating that increases and decreases in energy consumption exert significantly different long-run effects on environmental degradation. In contrast, the null hypothesis of short-run symmetry cannot be rejected, suggesting that positive and negative changes in EC have statistically similar short-run effects.

Given the evidence of long-run asymmetry, the panel NARDL model was estimated. Table 6 presents the long-run and short-run estimation results. Overall, the estimated coefficients of real GDPpc, real GDPpc^2, POP, FDI, TO, and IND are broadly consistent in both sign and statistical significance with those obtained from the panel ARDL model, indicating that the main findings are robust to the nonlinear specification.

Table 6. Results of the EKC panel NARDL estimates.

	Dependent Variable: D(lnCO_2)			Dependent Variable: D(lnEFP)		
Variables	**Coefficient**	***t*-Statistic**	**Prob.**	**Coefficient**	***t*-Statistic**	**Prob.**
Long-run coefficients						
lnGDPpc	9.332 ***	9.286	0.000	−10.695 ***	−8.145	0.000
lnGDPpc^2	−0.549 ***	−6.695	0.000	1.298 ***	6.458	0.000
lnEC^{+}	0.912 ***	8.291	0.000	0.891 ***	14.371	0.000
lnEC^{-}	−0.605 ***	−4.515	0.000	0.595 ***	6.263	0.000
lnPOP	−0.115 *	−1.769	0.096	−0.128 *	−1.684	0.092
lnFDI	−0.466	−2.251	0.150	0.445	−1.382	0.161
lnTO	0.058 *	1.318	0.063	0.069 *	0.325	0.076
lnIND	0.489 *	1.294	0.078	−0.782 **	−2.031	0.043
Trend	−0.033 ***	−0.825	0.000	−0.010 ***	−1.667	0.000
Short-run coefficients						
ECT(-1)	−1.745 ***	−6.415	0.000	−1.486 ***	−8.793	0.000
D(lnGDPpc)	26.835	3.248	0.151	−59.656 **	−9.885	0.041
D(lnGDPpc(-1))	−30.749 **	−5.926	0.023	19.954	2.104	0.307
D(lnGDPpc^2)	−1.445	−5.088	0.261	1.558 **	0.363	0.092
D(lnGDPpc^2(-1))	1.069 **	2.391	0.025	0.533	2.348	0.379
D(lnGDPpc^2(-2))	0.912	1.842	0.247	0.059	0.278	0.342
D(lnEC)	0.563 ***	6.951	0.000	0.742 ***	7.649	0.002
D(lnEC(-1))	0.212 **	2.585	0.026	0.237 *	2.576	0.063
D(lnEC(-2))	0.115	0.235	0.382	0.111	2.018	0.753
D(lnPOP)	−3.842 ***	−2.531	0.002	−1.927 ***	1.746	0.001
D(lnPOP(-1))	2.049	2.678	0.361	1.624	2.297	0.346
D(lnPOP(-2))	1.130	1.192	0.334	0.978	0.885	0.269
D(lnFDI)	0.310	1.297	0.365	0.285 **	0.858	0.034
D(lnFDI(-1))	0.564 *	1.575	0.072	0.307	1.055	0.269
D(lnTO)	0.016	0.457	0.849	0.021	0.396	0.658
D(IND)	0.212 *	2.753	0.096	0.234 *	4.875	0.072
Constant	−6.398 ***	−3.276	0.000	−5.169 ***	−2.962	0.000

Note: Model selection was based on the AIC. The optimal lag structure for both the CO_2 emissions and EFP models was PMG (1,2,3,3,3,2,1,1). The superscripts "+" and "−" denote positive and negative partial-sum decompositions of the explanatory variables, respectively. *, **, and *** indicate statistical significance at the 10%, 5%, and 1% levels, respectively.

The long-run estimates based on CO_2 emissions support the EKC hypothesis. The positive coefficient of real GDPpc and the negative coefficient of its squared term indicate an inverted U-shaped relationship between economic growth and CO_2 emissions. Conversely, when the EFP variable is used as the environmental indicator, the coefficients imply a U-shaped relationship, thereby rejecting the EKC hypothesis, whereas economic growth has a positive and significant effect on environmental degradation in both the long run and the short run. This finding suggests that although economic development may improve carbon efficiency, broader ecological pressures associated with resource consumption continue to intensify as income rises. Consequently, relying solely on CO_2 emissions may underestimate the overall environmental impacts of economic growth.

The asymmetric long-run estimates further reveal that positive and negative changes in EC affect environmental degradation differently. For the CO_2 emissions model, the coefficient on positive EC shocks (EC+) is positive and statistically significant (0.912), whereas the coefficient on negative EC shocks (EC−) is negative and statistically significant (−0.605). These estimates indicate that increases in EC generate larger increases in CO_2 emissions than reductions achieved through equivalent decreases in energy consumption.

Specifically, a 1% increase in EC raises CO_2 emissions by approximately 0.912%, whereas an equivalent reduction lowers them by about 0.605% in the long run. This asymmetric response implies that environmental deterioration resulting from higher energy demand is more pronounced than the environmental gains obtained from reducing energy use. Similar evidence has been reported by Munir and Riaz [4,37], Alshehry and Belloumi [36], and Mujtaba and Jena [108]. In contrast, Mujtaba et al. [7] and Şanlı et al. [109] found that both positive and negative EC shocks deteriorate environmental quality, whereas Khan et al. [39] reported insignificant asymmetric effects.

For the EFP model, both positive and negative partial-sum components of EC are positive and statistically significant, with coefficients of 0.891 and 0.595, respectively. The Wald test confirms that these coefficients differ significantly, indicating asymmetric long-run effects. The larger coefficient associated with positive EC shocks suggests that increases in EC exert a stronger influence on ecological degradation than reductions in EC. These findings imply that while lowering EC contributes to reducing ecological pressure, the environmental benefits are relatively smaller than the ecological costs generated by increased energy demand. This asymmetry likely reflects the continued dependence of Southeast Asian economies on fossil fuel-based energy systems and the persistence of other drivers of ecological degradation, including industrial expansion, land-use change, and intensive resource extraction. Similar conclusions have been reported by Baz et al. [10] and Mujtaba et al. [76], who documented asymmetric effects of EC on environmental quality.

The short-run estimates indicate that EC has a positive and statistically significant impact on both CO_2 emissions and the EFP, confirming that increases in energy demand immediately intensify environmental degradation. Moreover, the error correction terms (ECT(-1)) are negative and highly significant in both models (-1.745 for CO_2 emissions and -1.486 for the EFP), confirming the existence of a stable long-run equilibrium relationship among the variables.

4.7. Robustness Checks

To provide robust checks on the panel ARDL-PMG estimation results, FMOLS, DOLS, and CCR methods are used to assess the existence of a long-run relationship among the variables. Results of these estimators are presented in Table 7. All estimators are very similar in sign and significance, yielding findings consistent with the panel ARDL-PMG estimation methods and thereby confirming the robustness of the panel ARDL-PMG estimators. The empirical evidence shows that all estimators exhibit significant explanatory power, with adjusted R^2 values of 0.976 (FMOLS), 0.975 (DOLS), and 0.972 (CCR). These results indicate that the adjusted R^2 explains approximately 97% of the variation in the dependent variable. The R^2 and adjusted R^2 values thus confirm the fitness of the model specifications.

Based on CO_2 emissions, the EKC is confirmed by panel FMOLS, DOLS, and CCR estimators, indicating that real GDPpc has a significant positive relationship with CO_2 emissions, while $GDPpc^2$ shows a significant negative relationship. Nevertheless, when the EFP variable is taken into account, the panel FMOLS, DOLS, and CCR estimators confirm the invalidation of the EKC, with real GDPpc displaying a substantially negative relationship and $GDPpc^2$ showing a significant positive relationship with EFP. As shown in the panel ARDL results, POP appears to play a pivotal role in reducing both CO_2 emissions and EFP in Southeast Asian countries, whereas TO is associated with increases in both CO_2 emissions and EFP. Meanwhile, contrasting findings are also observed in panel FMOLS, DOLS, and CCR models for EC, FDI, and IND, thereby reinforcing the panel ARDL results. Thus, we can infer that our empirical panel ARDL results are trustworthy and can be interpreted with confidence.

Table 7. Results of the panel FMOLS, DOLS, and CCR estimations.

Dependent Variable: D(lnCO$_2$)									
	FMOLS			DOLS			CCR		
Variables	**Coeff.**	**Std. Err.**	**Prob.**	**Coeff.**	**Std. Err.**	**Prob.**	**Coeff.**	**Std. Err.**	**Prob.**
lnGDPpc	3.595 ***	0.040	0.000	3.662 ***	0.050	0.000	3.968 ***	0.056	0.000
lnGDPpc^2	−0.205 ***	0.016	0.002	−0.218 ***	0.055	0.000	−0.224 ***	0.033	0.000
lnEC	0.365 ***	0.039	0.001	0.339 ***	0.043	0.000	0.395 ***	0.062	0.000
lnPOP	−0.259 ***	0.022	0.003	−0.128 ***	0.032	0.006	−0.282 **	0.024	0.005
lnFDI	0.036 ***	0.008	0.000	−0.006 *	0.016	0.097	−0.002 *	0.010	0.065
lnTO	0.034 *	0.031	0.082	−0.032	0.075	0.354	0.049 *	0.035	0.078
lnIND	−0.185 *	0.096	0.057	0.265 ***	0.158	0.000	0.172 *	0.123	0.069
R^2	0.976			0.975			0.972		
Adj. R^2	0.971			0.970			0.970		
Dependent Variable: D(lnEFP)									
	FMOLS			**DOLS**			**CCR**		
Variables	**Coeff.**	**Std. Err.**	**Prob.**	**Coeff.**	**Std. Err.**	**Prob.**	**Coeff.**	**Std. Err.**	**Prob.**
lnGDPpc	−1.857 ***	0.005	0.000	−2.161 ***	0.004	0.000	−1.798 ***	0.023	0.000
lnGDPpc^2	0.268 ***	0.011	0.002	0.305 ***	0.005	0.003	0.295 ***	0.005	0.000
lnEC	0.069 **	0.032	0.045	−0.146 ***	0.090	0.006	0.078 **	0.065	0.042
lnPOP	−0.397 ***	0.010	0.000	−0.551 ***	0.007	0.000	0.442 ***	0.028	0.001
lnFDI	0.013 ***	0.005	0.009	−0.011	0.066	0.258	0.015 ***	0.078	0.006
lnTO	0.077 ***	0.023	0.000	−0.058	0.097	0.172	0.082 **	0.020	0.048
lnIND	−0.104	0.078	0.328	−0.095	0.096	0.285	−0.115	0.035	0.342
R^2	0.975			0.974			0.972		
Adj. R^2	0.971			0.970			0.968		

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

4.8. The Dumitrescu–Hurlin Panel Causality Test

The integrated Dumitrescu–Hurlin [110] panel causality results in Table 8 reveal several common patterns across the two environmental indicators (i.e., CO_2 emissions and EFP). Real GDPpc, EC, and POP show bidirectional causality with both indicators, suggesting strong feedback among economic activity, resource use, demographic pressures, and environmental degradation. These findings imply a mutually reinforcing relationship between environmental quality and economic development in Southeast Asian countries.

Table 8. Results of the Dumitrescu–Hurlin panel causality test: CO_2 emissions versus EFP.

Variables	lnCO$_2$	lnEFP
lnGDPpc ↔ Environmental Indicator	Feedback	Feedback
lnEC ↔ Environmental Indicator	Feedback	Feedback
lnPOP ↔ Environmental Indicator	Feedback	Feedback
lnFDI ↔ Environmental Indicator	Unidirectional: lnFDI → lnCO$_2$	Unidirectional: lnFDI → lnEFP
lnTO ↔ Environmental Indicator	Unidirectional: lnTO → lnCO$_2$	No causality
lnIND ↔ Environmental Indicator	Feedback	Unidirectional: lnIND → lnEFP

Note: Feedback indicates bidirectional causality between the variables. Unidirectional indicates one-way causality from the explanatory variable to the environmental indicator. No causality indicates the absence of statistically significant causal relationships in either direction. The lag length for all variables is 1.

FDI exerts a unidirectional causal effect on both CO_2 emissions and EFP, indicating that investment inflows influence environmental outcomes without significant reverse feedback. TO, however, shows heterogeneous effects across the two indicators. Specifically, TO increases CO_2 emissions but shows no significant causal relationship with EFP, suggesting that the environmental consequences of trade are more directly reflected in carbon emissions than in broader ecological pressures. Regarding IND, the results indicate bidirectional causality with CO_2 emissions, whereas a unidirectional causal relationship runs from IND to EFP. This finding suggests that industrial activities and carbon emissions are closely interconnected, while industrialization primarily drives ecological pressure, with little feedback from EFP.

Overall, the causality analysis highlights the pivotal roles of economic growth, energy consumption, and population dynamics in shaping environmental degradation and underscores the need for policies that promote sustainable energy use, green industrial transformation, and environmentally responsible investment strategies to achieve long-term sustainable development in the region.

5. Conclusions and Policy Implications

This study examined the effects of economic growth and energy consumption on environmental degradation in nine Southeast Asian countries during 1990–2022 using linear and nonlinear panel techniques. The findings show that economic growth and energy consumption remain key drivers of environmental degradation, although their impacts differ depending on the environmental indicator employed. While the EKC hypothesis is supported when environmental degradation is measured by CO_2 emissions, it is not supported when the ecological footprint is used, highlighting the importance of adopting multidimensional indicators in environmental sustainability research. However, the differing EKC results suggest that economic growth may be accompanied by improvements in carbon efficiency, while broader pressures on natural resources persist. This implies that reductions in CO_2 emissions do not necessarily translate into improvements in overall environmental sustainability, as reflected by the ecological footprint. These findings are robust to alternative cointegration estimators, including FMOLS, DOLS, and CCR. By simultaneously examining CO_2 emissions and the EFP within a unified analytical framework, this study contributes new evidence to the environmental sustainability literature and extends existing research on Southeast Asian economies.

Given the considerable differences in income levels, industrial structures, and energy systems across the nine Southeast Asian countries, a uniform policy approach is unlikely to achieve optimal environmental outcomes. The findings suggest that environmental policies should reflect the diverse economic structures and development levels of Southeast Asian countries. High-income economies such as Singapore and Brunei Darussalam should prioritize technological innovation, improvements in energy efficiency, deployment of renewable energy, and market-based carbon mitigation instruments to further reduce emissions while maintaining economic competitiveness. Upper-middle-income economies, including Malaysia and Thailand, should accelerate industrial decarbonization by promoting energy-efficient manufacturing, expanding renewable energy capacity, and strengthening environmental regulations for energy-intensive industries. Developing economies such as Cambodia, Indonesia, Myanmar, the Philippines, and Vietnam should focus on reducing dependence on fossil fuels by expanding access to affordable renewable energy, improving energy infrastructure, strengthening environmental governance, and attracting green foreign direct investment. Across the region, greater ASEAN cooperation in renewable energy investment, technology transfer, cross-border electricity interconnections, and harmonized environmental standards would further support the transition toward sustainable and low-carbon development. Because the EKC is supported only when environmental degradation is measured by CO_2 emissions, policymakers should complement carbon mitigation strategies with policies promoting sustainable resource management, efficient land use, and resource efficiency to address the broader environmental pressures captured by the ecological footprint.

This study demonstrates that evaluating environmental sustainability solely through CO_2 emissions may underestimate the broader environmental impacts of economic growth. Incorporating ecological footprint alongside conventional emissions indicators provides a more comprehensive evaluation of environmental sustainability and supports more effective policy design.

Future research could extend this study by investigating country-specific nonlinear dynamics, incorporating additional environmental indicators, and examining how institutional quality, renewable energy adoption, and technological innovation influence the growth–environment nexus across Southeast Asia. More broadly, the findings indicate that conclusions regarding the validity of the EKC depend critically on the environmental indicator employed. Consequently, future research and environmental policy evaluations should adopt multidimensional measures of environmental sustainability to better capture the complex interactions among economic growth, energy consumption, and environmental degradation.

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Appendix A

Table A1. Description and sources of the selected variables.

Variables	Measurement	Acronym	Source
Ecological footprint	Ecological footprint (global hectares per capita)	EFP	GFN [78]
Carbon dioxide emissions	CO_2 emissions (metric tons per capita)	CO_2	WDI [79]
Energy consumption	Energy consumption (kg of oil equivalent per capita)	EC	WDI [79]
Economic growth	GDP per capita (constant 2015 US$)	GDPpc	WDI [79]
Population density	Population density (people per sq. km of land area)	POP	WDI [79]
Foreign direct investment	FDI, net inflows (% of GDP)	FDI	WDI [79]
Trade openness	Trade openness as the sum of exports and imports to GDP	TO	WDI [79]
Industrialization	Manufacturing sector added value (% of GDP)	IND	WDI [79]

Note: WDI: World Development Indicators. GFN: Global Footprint Network.

Table A2. Results of the Westerlund panel cointegration test.

Model 1: $lnCO_2 = f(lnGDPpc, lnGDPpc^2, lnEC, lnPOP, lnFDI, lnTO, lnIND)$			
Statistic	Value	Z-value	*p*-value
Gτ	−2.987 ***	−1.512	0.000
Gα	−7.135	1.583	1.000
Pτ	−5.958 ***	−1.236	0.000
Pα	−3.586	1.784	1.000
Model 2: $lnEFP = f(lnGDPpc, lnGDPpc^2, lnEC, lnPOP, lnFDI, lnTO, lnIND)$			
Statistic	Value	Z-value	*p*-value
Gτ	−3.228 ***	−2.015	0.000
Gα	−7.495	1.932	1.000
Pτ	−5.788 ***	−1.512	0.000
Pα	−3.595	1.597	1.000

Note: Gτ and Gα denote the group-mean statistics, whereas Pτ and Pα denote the panel statistics. Optimal lag and lead lengths are selected using the AIC. *** indicates rejection of the null hypothesis at the 1% significance level.

Table A3. Results of the Hausman test for the MG and PMG Estimators.

	Coefficients			
	(b) MG	**(B) PMG**	**(b-B) Difference**	**sqrt (diag (V_b-V_B)) S.E.**
lnGDPpc	−37.784	2.508	−40.292	119.541
$lnGDPpc^2$	1.911	−0.135	2.046	5.760
lnEC	0.329	0.278	0.051	0.361
lnPOP	2.825	0.984	1.841	8.394
lnFDI	0.033	0.012	0.021	0.057
lnTO	−0.038	0.187	−0.225	0.398
lnIND	−0.526	−0.005	−0.521	1.271
Chi2(7) = (b-B)′[(V_b-V_B)$^{-1}$] (b-B) = 4.28; Prob > Chi2 = 0.654				

Note: b is consistent under H0 and Ha; obtained from xtpmg. B is inconsistent under Ha and efficient under H0; obtained from xtpmg. Test: H0: the difference in coefficients is not systematic.

Table A4. Symmetry test results.

Variable	**Null Hypothesis: Coefficient Is Symmetric**			
	Long-Run Symmetry		**Short-Run Symmetry**	
	Statistic	**Prob.**	**Statistic**	**Prob.**
lnEC	56.402 ***	0.000	11.695	0.372

Note: *** indicates rejection of the null hypothesis of symmetry at the 1% significance level.

Appendix B

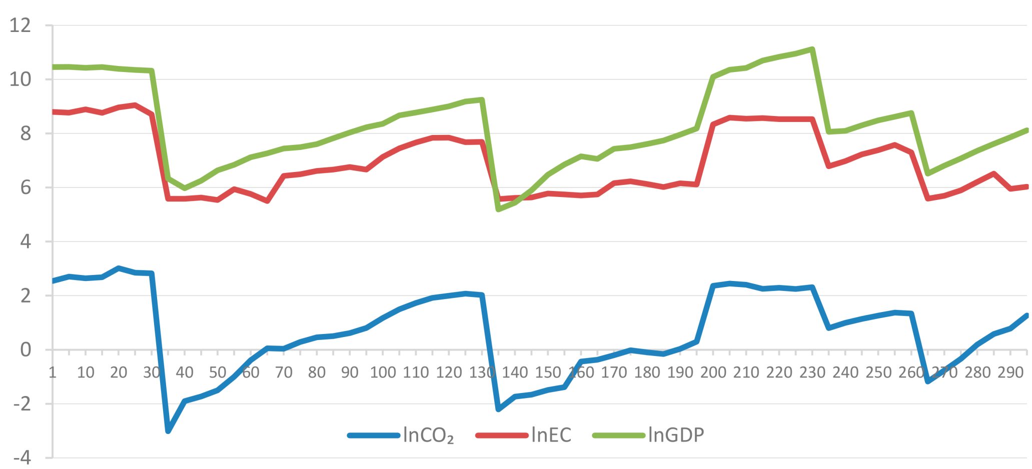

Figure A1. CO_2 Emissions–real GDPpc–EC Nexus. Source: Author’s own elaboration.

https://doi.org/10.3390/su18157532

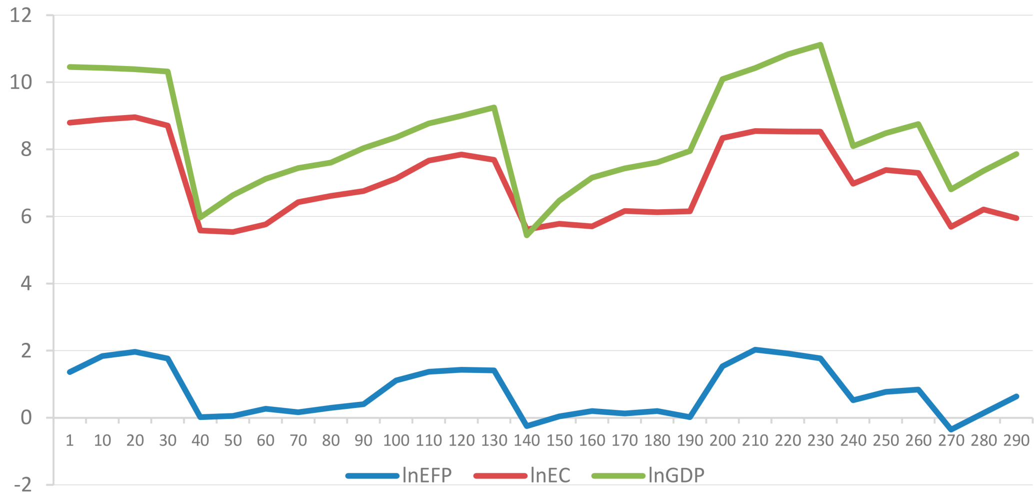

Figure A2. EFP–real GDPpc–EC Nexus. Source: Author's own elaboration.

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