Revisiting the Environmental Kuznets Curve: The Impact of Economic Growth and Trade Openness on CO_2 Emissions in Southeast Asian Countries

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Abstract

Research purpose:

This study aims to investigate the impact of economic growth and trade openness on CO_2 emissions across eight Southeast Asian countries from 1990 to 2022. The non-linear impact was examined by testing the Environmental Kuznets Curve (EKC) hypothesis, seeking to determine whether rising income levels in the region eventually contribute to environmental improvement or exacerbate environmental pressures.

Research motivation:

As Southeast Asia has become one of the most vibrant regions in the world, it has also faced severe environmental problems. This has raised the concerns about sustainability and the nature of the relationship between economic growth and environmental improvement. Although the EKC hypothesis has been widely studied elsewhere, evidence from Southeast Asia remains limited and inconclusive. Therefore, it is necessary to explore whether countries in the region are in good bath ways to balance growth with environmental protection.

Research design, approach, and method:

The study employs annual data from 1990 to 2022 for eight Southeast Asian economies, utilizing panel regression models to assess both quadratic and cubic specifications of the Environmental Kuznets Curve (EKC). This method may identify nonlinear relationships between income growth and CO_2 emissions, as well as demonstrate the impact of trade openness on these relationships. Separate country analyses are conducted to highlight differences in economic structures, policy settings, and development stages.

Main findings:

The findings reveal a mixed picture. While the EKC framework is confirmed in the cases of Thailand, Malaysia, Singapore, and Cambodia, showing a eventual decline in emissions beyond certain income thresholds, others, notably Vietnam and Brunei, do not follow this trajectory. The impact of trade openness on CO_2 emissions also varies among the countries in Southeast Asia.

Practical/managerial implications:

The findings significantly impact both corporate executives and legislators. Governments emphasize the necessity of integrating sustainability into development plans by investing in renewable energy, enhancing energy efficiency, and enforcing environmental regulations more rigorously. For firms, the results emphasize green technology adoption as well as compliance with international sustainability standards.

Keywords: CO_2 emissions, Economic growth, Trade openness, Environmental Kuznets Curve, Southeast Asia.

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1. INTRODUCTION

In recent years, environmental issues have emerged as a significant worldwide concern due to their profound and extensive impacts. A significant issue confronting the globe today is climate change, which poses threats to the economy, communities, and ecosystems globally. The incidence and intensity of extreme weather phenomena, including hurricanes, heat waves, droughts, and floods, are escalating. Numerous people and businesses worldwide have already suffered as a result of these disasters. People in underdeveloped nations who are already frail are the ones that suffer the most from this. This exacerbates inequality and jeopardizes global security. In this instance, addressing the underlying causes of climate change has emerged as a critical issue for both economic and environmental reasons.

The emission of carbon dioxide (CO_2) is one of the primary causes of global warming. These emissions are mostly caused by burning fossil fuels, operating manufacturing, and driving automobiles. The global economy is impacted by these pollutants in two ways. They are a useful tool for monitoring the amount of energy and money that people are using, and they demonstrate the extent of commerce, consumption, and industrialization. Nevertheless, they are the primary cause of the greenhouse effect, which exacerbates climate change. This paradox makes it crucial to consider the relationship between CO2 emissions and economic growth. It is essential to understand this link to formulate strategies that reconcile environmental conservation with economic development.

The Environmental Kuznets Curve (EKC) theory is a prominent approach for analyzing this relationship. The Environmental Kuznets Curve (EKC) posits an inverse U-shaped correlation between economic growth and environmental degradation: pollution rises initially during the nascent phases of industrialization, but upon surpassing a specific income threshold, economic growth results in enhancements in environmental quality, attributed to technological advancements, more stringent regulations, and increased public awareness. Nevertheless, actual investigations concerning the Environmental Kuznets Curve (EKC) have yielded incongruous findings, especially for CO_2 emissions, which are a global rather than a localized pollutant. Some nations have exhibited linear or N-shaped trajectories, while others have demonstrated the expected inverted U-shape. This underscores the need for further investigation in specific domains. Besides income growth, trade liberalization significantly influences environmental outcomes. Economic integration, illustrated by trade liberalization, foreign direct investment, and participation in global supply chains, may intensify emissions by fostering industrial activity, as posited by the "pollution haven hypothesis." Nonetheless, the promotion of green technologies, environmental restrictions, and efficiency enhancements can facilitate cleaner production. This is referred to as the "pollution halo hypothesis." The eventual effect of openness depends on each nation's developmental status, law enforcement efficacy, and technology expertise.

Southeast Asia is an essential region for analyzing these developments. The region is marked by swift industrialization, heightened urbanization, and greater engagement in the global economy. Nonetheless, the probability of extreme weather, escalating sea levels, and environmental degradation is intensifying, rendering it one of the most climate-vulnerable regions on the planet. Consequently, regional governments and politicians are prioritizing the equilibrium between sustainable economic growth and climate change mitigation.

This study is guided by two primary research questions: Initially, what is the relationship between GDP and CO_2 emissions in Southeast Asian nations? Secondly, does the Environmental Kuznets Curve (EKC) exist in this location, and if so, what type of relationship does it demonstrate? The responses to these inquiries should assist in ascertaining whether economic growth in Southeast Asia consistently correlates with heightened emissions or if this association is mitigated by structural and regulatory influences.

This study aims to empirically evaluate the validity of the Environmental Kuznets Curve (EKC) hypothesis and determine the per capita income threshold at which CO_2 emissions may commence their decline, by examining the relationships among economic growth, trade openness, and CO_2 emissions in eight Southeast Asian nations. Furthermore, it seeks to elucidate the diverse impacts of trade openness on emissions dynamics, specifically whether it aggravates or alleviates them. This study enhances academic and policy discourse on how emerging and developing economies may sustain economic stability while implementing green growth strategies.

The analysis encompasses the years 1990 to 2022, a crucial era of industrialization and regional integration marked by the COVID-19 epidemic, the global financial crisis of 2008, and the Asian Financial Crisis of 1997 to 1998. The eight chosen nations are Brunei Darussalam, Vietnam, Thailand, Malaysia, Singapore, the Philippines, Indonesia, and Cambodia. The sample is diversified, encompassing diverse economic systems, environmental legislation, and stages of development.

The study employs quantitative econometric approaches utilizing annual panel data from esteemed institutions such as the World Bank, the International Monetary Fund, and the United Nations. This study employs quadratic and cubic regression models within a panel data framework to investigate the presence of nonlinear Environmental Kuznets Curve (EKC) dynamics and the influence of trade openness as an additional explanatory variable. This approach ensures robust results, facilitating the assessment of income thresholds and the comparison of nations.

This study offers both theoretical and practical contributions. By supplying data from Southeast Asia, a region with limited research relative to Europe, North America, or East Asia, it theoretically enhances the empirical literature on the Environmental Kuznets Curve (EKC). The work also tackles criticisms of oversimplification in EKC modeling by analyzing both quadratic and cubic specifications. The findings offer a scientific basis for the decisions made by regional leaders. Assessing the correlation between CO_2 emissions reduction and income growth is beneficial for climate action.

An awareness of how trade openness influences trade agreements, foreign investment, and technology transfer facilitates the development of strategies in these domains. The study enhances the discourse on sustainable development by emphasizing the importance of integrating environmental factors into economic strategy.This work provides both theoretical and practical contributions. By providing data from Southeast Asia, a region with limited research compared to Europe, North America, or East Asia, it theoretically enriches the empirical literature on the Environmental Kuznets Curve (EKC).

The research addresses criticisms regarding the simplicity of Environmental Kuznets Curve modeling by evaluating both cubic and quadratic specifications. The findings provide municipal governments with a robust scientific foundation. Examining the impact of trade openness on trade agreement strategy, foreign investment, and technology transfer, alongside assessing the conditions under which CO_2 emissions decline as income rises, yields critical insights for climate action. The study advances the discourse on sustainable development by emphasizing the necessity of incorporating environmental considerations into economic strategy.

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2. LITERATURE REVIEW

2.1 Concept of Environmental Kuznets Curve

According to the Environmental Kuznets Curve (EKC) theory, there is an inverse U-shaped relationship between per capita income and environmental pollution. Because of advancements in technology and sound environmental regulations, pollution tends to decrease after a particular wealth level is attained, although it typically increases with economic expansion. However, empirical studies pertaining to the EKC have produced erratic and often conflicting results.

An effective method for examining the connection between income and environmental harm is the EKC framework. Urbanization, energy consumption, and industry frequently result in increased CO_2 emissions during the early phases of growth. Technology advancements, more environmental consciousness, and more stringent policy enforcement can all contribute to reducing emissions and improving the environment after income exceeds a particular threshold. Therefore, economic expansion has the potential to both improve and harm the environment.

Under these circumstances, it is widely expected that CO_2 emissions will be positively correlated with trade liberalization or income before the inflection point and negatively correlated after. While positive connections can indicate insufficient trade liberalization or ineffective policy, negative correlations might indicate that greater global integration makes it easier to obtain cleaner technologies and stricter environmental restrictions. However, because different approaches, situations, and contaminants were evaluated, the data is still equivocal.

The failure of earlier EKC research to adequately account for the variation in developmental stages among nations is a serious flaw. This has produced contradictory findings about the functions of trade openness and GDP. Developing economies must make more trade-offs between sustainability and growth since they rely heavily on resource-intensive and fossil fuel-using businesses. However, industrialized economies might have already made the transition to greener habits and technologies, which alters the EKC's trajectory.

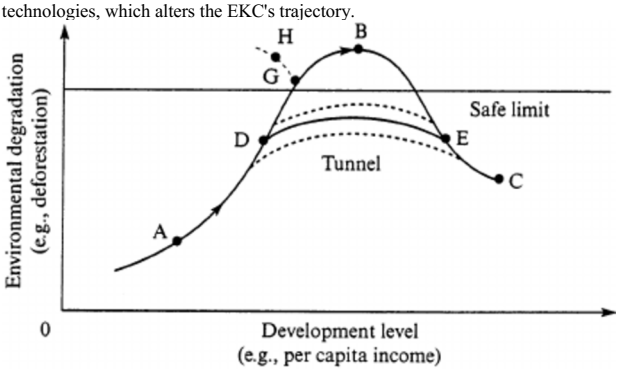

Fig. 1. Tunnelling through the environmental Kuznets curve using sustainable development strategies

(Source: Munasinghe, M. (1999))

According to this perspective, Southeast Asia provides a diverse testing ground for the EKC hypothesis. The nations in the region have economies at varying phases of development, ranging from rapidly industrializing nations to those with a greater emphasis on services. This diversity results in varying energy consumption patterns, trade openness levels, and regulatory frameworks, all of which have an impact on CO2 emissions.

Additionally, the consequences of climate change, such as rising sea levels, extreme weather, and risks to food security, are particularly dangerous for Southeast Asia. Finding a balance between environmental preservation and economic growth is even more crucial in light of these issues. In addition to being of academic interest, policymakers

also need to understand the relationships between growth, emissions, and openness in order to make wise decisions. We can determine whether trade liberalization promotes cleaner production and the adoption of new technology or increases our reliance on carbon-intensive industries by examining the EKC in this regional context. Policymakers can use this study to develop strategies that strike a compromise between climate goals and economic integration. Additionally, it can contribute to the broader discussion regarding how to accomplish sustainable development in underdeveloped nations.

2.2 The Environmental Kuznets Curve in the Context

This research investigates the applicability of the Environmental Kuznets Curve (EKC) in eight Southeast Asian countries. The EKC hypothesis suggests that the relationship between economic growth, commonly measured by GDP per capita, and environmental pollution follows an inverted U-shape. In other words, pollution tends to rise during the early stages of economic expansion, reaches a peak at a certain income threshold, and eventually declines as economies continue to grow.

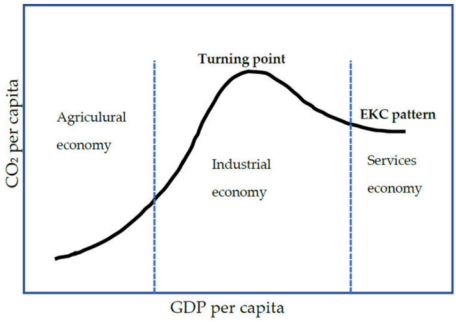

Fig. 2.Environmental Kuznets Curve (EKC): Relationship Between GDP per Capita and CO2 Emissions

(Source: Munasinghe, M. (1999))

Table 1. Stages of the Environmental Kuznets Curve (EKC) and Impact Channels

Stage	Relationship Direction	Impact Channel/Explanation
Initial Stage	Positive	Rapid industrialization, heavy reliance on fossil fuels, urbanization, deforestation, and expansion of manufacturing sectors, heavy industry. Early adoption of green economic strategies
Turning Point (Threshold)	Negative	Implementation of stronger environmental policies, increased energy efficiency, growing investments in renewable energy, and stricter global trade environmental standards.
Subsequent Stage	Negative	Full integration of environmental sustainability into policies, high public awareness, adherence to international environmental treaties, and widespread adoption of renewable energy technologies

(Author's Synthesis)

The process can be described in three main stages. First, during the initial stage, rapid industrialization, reliance on heavy industries, and extensive use of fossil fuels drive up pollution levels. At this point, growth objectives take precedence over environmental concerns. Second, at the turning point, rising incomes allow societies and governments to allocate resources toward cleaner technologies, environmental regulations, and sustainability initiatives. Awareness of environmental risks also becomes more widespread, shifting priorities toward long-term well-being. Finally, in the subsequent stage, continued economic growth is accompanied by declining pollution levels, driven by technological advancements, stricter policies, structural changes in the economy, and both domestic and international pressure to improve environmental performance.

Notwithstanding its intuitive allure, the Environmental Kuznets Curve (EKC) continues to be contentious. Although

some studies validate the inverted U-shaped correlation for specific local pollutants like sulfur dioxide and particulate matter, numerous others indicate divergent patterns, including monotonic rises, N-shaped curves, or an absence of a definitive association altogether. Critics contend that the Environmental Kuznets Curve (EKC) is underpinned by feeble empirical underpinnings, highlighting methodological deficiencies and data constraints. Evidence supporting the Environmental Kuznets Curve (EKC) is notably scarce regarding global pollutants such as CO_2, where linear or consistently ascending patterns are frequently detected.

The validity of the EKC depends on several aspects, particularly within the Southeast Asian environment. The characteristics of the contaminant are crucial. This study examines CO_2, a worldwide contaminant with little empirical support for the Environmental Kuznets Curve (EKC). The national context, encompassing a nation's developmental status, industrial composition, institutional robustness, and cultural perspectives, can influence the outcomes. The methodological approach may yield varying results depending on the econometric techniques utilized. The duration of the investigation is crucial, as technological and legal advancements over decades may alter the relationship between growth and pollution.

These constraints highlight important debates. The Environmental Kuznets Curve (EKC) should not be regarded as a universal principle, as it does not operate uniformly across all pollutants or nations. It addresses correlation rather than causality, raising inquiries on the underlying systems. The EKC paradigm also presents ethical dilemmas: it implies that developing nations must endure a phase of elevated pollution prior to achieving environmental enhancement, which may not constitute a viable or sustainable solution.

The EKC framework remains ambiguous regarding CO_2 emissions. The swift economic expansion, significant dependence on fossil fuels, and varied national circumstances of Southeast Asia render it an essential case study for evaluating the validity of the Environmental Kuznets Curve (EKC). This study aims to provide new empirical insights into the growth-emissions relationship in one of the world's most dynamic regions by examining data from eight countries.

2.3 Literature review

Existing EKC studies in the EU, BRICS, and China/India have given us important information, but Southeast Asia is still different in terms of its energy structure, reliance on industries, and level of policy maturity. This part focuses on two groups of literature review: (1) The impact of economic growth on CO2 emissions; (2) The impact of trade openness on CO2 emissions.

Research investigating the relationship between GDP and CO2 emissions under the Environmental Kuznets Curve (EKC) framework has produced ambiguous findings. Chandran and Tang (2013) focused on China and India, demonstrating short-term causation from GDP to CO2 emissions in China and long-term causality from coal to GDP in both countries, emphasizing the critical role of coal in sustaining long-term economic growth. However, their research did not explicitly assess the inverted U-shape proposed by the EKC. Kasman and Duman (2015) investigated EU member and candidate nations, revealing cointegration and causality among energy consumption, GDP, CO2 emissions, trade, and urbanization, so demonstrating the complex interplay between economic and environmental variables within the European context. Dong et al. (2018) demonstrated short-term causation from GDP to renewable energy consumption and long-term causation from renewable energy to CO2 emissions in China, highlighting the persistent importance of renewable energy in reducing emissions. These studies do not directly evaluate the inverted U-shape of the Environmental Kuznets Curve; however, they provide significant insights, illustrating that the relationship between economic growth and emissions is heavily affected by contextual factors, such as energy systems and developmental pathways.

Table 2. Stages of the Environmental Kuznets Curve (EKC) and Impact Channels

No.	Authors	Variables	Time period	Methodology	Coin.	Causation
1	Hdom & Fuinhas (2020) [33]	GDP, CO2, Hydro, NatG, RE, Open	1970–2017, Brazil	FMOLS, DOLS	Yes	SR: Trade → Energy; LR: GDP ↔ CO2
2	Yang et al. (2022) [34]	REC, GN, GDP, TO, ROP, CO2	1991–2020, OECD countries	AMG Estimator	Yes	SR: GDP → RE; LR: GDP ↔ RE
3	Hossain (2011) [35]	CO2, EN, Open, PGDP, UR	1971–2007, Newly Industrialized Countries (NICs)	Johansen Fisher Panel Cointegration, Granger Causality	Yes	SR: Trade → CO2; LR: GDP → Energy
4	Dong et al. (2018) [36]	CO2, FF, NU, RE, GDP	1993–2016, China	Structural Break Tests	Yes	SR: GDP → RE; LR: RE → CO2
5	Kasman & Duman (2014) [37]	EC, GDP, CO2, Trade, Urban	1992–2010, EU new member and candidate countries	Panel Cointegration, Panel Causality	Yes	SR: Urban → GDP; LR: GDP ↔ CO2
6	Chandran & Tang (2013) [38]	CO2, GDP, Coal	1965–2009, China and India	Cointegration, Granger Causality	Yes (only China)	SR: GDP → CO2; LR: Coal ↔ GDP
7	Chen et al. (2019) [39]	CO2, GDP, RE, NRE, Trade	1980–2014, China	ARDL, VECM	Yes	SR: Trade ↔ CO2; LR: RE → CO2
8	Sebri & Ben-Salha (2014) [40]	GDP, REC, CO2, TO	1971–2010, BRICS countries	ARDL, VECM	Yes	SR: RE ↔ GDP; LR: RE ↔ GDP

Note for the abbreviation: GDP = Gross Domestic Product; CO2 = Carbon dioxide emissions; Hydro = Hydropower; NatG = Natural Gas; RE = Renewable Energy; Open = Trade Openness; REC = Renewable Energy Consumption; GN = Gross National Income; TO = Trade Openness; ROP = Real Oil Prices; EN = Energy Consumption; UR = Urbanization; PGDP = Per Capita GDP; FF = Fossil Fuels; NU = Nuclear Energy; EC = Energy Consumption; NRE = Non-Renewable Energy; ARDL = Autoregressive Distributed Lag model; VECM = Vector Error Correction Model; FMOLS = Fully Modified Ordinary Least Squares; DOLS = Dynamic Ordinary Least Squares; AMG = Augmented Mean Group Estimator. The arrows (→ and ↔) represent the direction of causality, while the absence of an arrow indicates no causality

(Author's Synthesis)

Previous studies examining the relationship between economic growth, trade openness, and CO_2 emissions have primarily focused on developed regions such as the European Union (EU) or large emerging economies such as BRICS and China. For China, empirical findings have confirmed the existence of the EKC; however, most studies rely on pre-COVID-19 data and fail to reflect recent socioeconomic dynamics, particularly the impact of green recovery policies and the restructuring of the energy sector. Moreover, the EKC represents a dynamic process influenced by factors such as structural transformation, environmental regulations, and trade integration—yet these dimensions have not been comprehensively addressed, leaving conclusions rather preliminary and context-specific.

In the EU, prior works often report a nonlinear relationship between growth and emissions, confirming the EKC hypothesis. Nevertheless, since EU economies are already in a post-industrial phase, their findings are difficult to generalize to developing economies where production structures remain heavily dependent on fossil fuels. Within BRICS, recent studies from Brazil, Russia, and South Africa suggest that renewable energy contributes positively to economic growth and emission reduction. However, these studies mainly identify causal links without exploring mediating mechanisms such as trade dynamics or environmental policy frameworks. Similarly, in India, results indicate short-run causality among growth, energy use, and emissions but lack evidence of long-run effects, partly due to limited data coverage and outdated time spans.

In contrast, Southeast Asia exhibits distinct economic and energy characteristics compared to the EU, BRICS, or China. ASEAN economies are in transition between industrialization and service-based development, marked by uneven structures, high export dependency, and reliance on fossil fuels. Moreover, the region faces increasing exposure to global energy price volatility and commitments under COP26. Despite these challenges, existing research on the growth–trade–emission nexus in Southeast Asia remains fragmented, often country-specific and based on pre-2020 data. There is still a lack of comprehensive, multi-country analysis using recent data and advanced econometric approaches to validate the EKC for ASEAN as a whole. This constitutes a critical research gap that the present study aims to address by providing updated empirical evidence that better reflects the region's evolving energy–environment dynamics in the current global context. Besides, while the economies of the EU and BRICS have mostly moved on from industrialization, the countries in ASEAN have to deal with two problems: keeping up their growth and cutting down on emissions, even though their institutions aren't all that strong. There are very few multi-country ASEAN EKC studies that use data from after 2020, especially those that look at trade openness as an interactive factor. This gap has led to the current study..

Overall, the prior studies have provided valuable insights into the relationship between CO2 emissions, economic growth, and trade openness in various contexts of economies and regions. However, there still exists a research gap for the case of the Southeast Asian region. This area is experiencing rapid economic growth and deep trade integration, with economies ranging from resource-based to manufacturing-oriented structures. At the same time, it is particularly vulnerable to the impacts of climate change.

Therefore, this research aims to:

1. Empirically analyze the relationship between economic growth, trade openness, and CO2 emissions in eight Southeast Asian countries using appropriate econometric methods.

2. Consider the heterogeneity across countries in terms of economic structures, environmental policies, energy sources, and other contextual factors.

3. Contribute to the development of sustainable policies for the region by providing empirical evidence on the impact of growth and trade on emissions within the specific Southeast Asian context.

3. METHODOLOGY

3.1 Specification of Environmental Kuznets curve

This study defines and measures the Environmental Kuznets Curve (EKC) for Southeast Asian countries from 1993 to 2023. The objective is to examine the existence of a nonlinear relationship between GDP and CO2 emissions, while simultaneously accounting for the influence of trade openness. This analysis aims to provide critical insights for setting environmental goals and promoting sustainable development policies in the region. The EKC hypothesis posits an inverted U-shaped relationship between economic expansion and environmental degradation. This indicates that environmental pollution increases with economic growth, peaks at a specific income level (the turning point), and subsequently declines as the economy continues to expand. Two main model specifications are employed to test for these relationships. The first model tests the inverted U-shaped relationship while assessing the impact of trade openness:

$$\ln(CO2_{it}) = \alpha_0 + \alpha_1 \ln(GDP_{it}) + \alpha_2[\ln(GDP_{it})]^2 + \alpha_3(OPEN_{it}) + \alpha_4(OPEN_{it})^2 + \epsilon_{it}$$

In this first model, the inverted U-shaped relationship is identified if:

1. The coefficient of the log of GDP ($\alpha 1$) is positive, indicating that CO2 emissions initially increase as GDP grows.
2. The coefficient of the squared log GDP term (α 2) is negative, suggesting that CO2 emissions decrease as GDP reaches a higher threshold. This would confirm the existence of the EKC, where environmental quality improves after achieving a certain level of economic development.

If $\alpha 2$ is positive, however, it suggests that CO2 emissions continue to rise with increasing GDP, invalidating the EKC hypothesis.

The second model extends the analysis to test for an N-shaped relationship by including a cubic term of log GDP:

$$\ln(CO2_{it}) = \beta_0 + \beta_1 \ln(GDP_{it}) + \beta_2[\ln(GDP_{it})]^2 + \beta_3[\ln(GDP_{it})]^3 + \beta_4(OPEN_{it}) + \beta_5(OPEN_{it})^2 + \eta_{it}$$

If $\beta 3$ is positive, it implies that after a period of decreasing CO2 emissions (the downward slope of the EKC), emissions

may rise again as GDP surpasses a higher threshold, reflecting the possibility of a rebound effect or challenges in sustaining environmental improvements.

Table 3.Description of variables and parameters

Variable	Description
$CO2_{it}$	CO2 emissions for country *i* at time *t* (logarithmic form).
GDP_{it}	GDP per capita for country *i* at time *t* (logarithmic form).
$OPEN_{it}$	Openness for country *i* at time *t*
$\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$	Coefficients in the first model to be estimated
$\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5$	Coefficients in the second model to be estimated.
ϵ_{it}	Error term in the first model, capturing unobserved factors affecting CO2 emissions.
η_{it}	Error term in the second model, capturing unobserved factors affecting CO2 emissions.

(Author's Synthesis)

Theoretically, the models expect that the inverted U-shaped relationship will be identified if the coefficient of log GDP (β1) is positive, while the coefficient of the squared log GDP term (β2) is negative. This indicates that CO2 emissions initially increase with GDP but then decrease as GDP reaches a higher threshold. Similarly, the N-shaped relationship will be determined if the coefficient of the cubic log GDP term (β3) is positive, suggesting that after CO2 emissions decrease, they may rise again as GDP grows beyond a certain level. This "turning point" concept is central to the EKC literature (4).

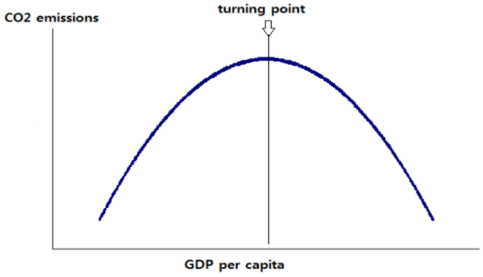

Fig. 3. Classic Inverted U-shaped EKC (Environmental Kuznets Curve)

(Source: Munasinghe, M. (1999))

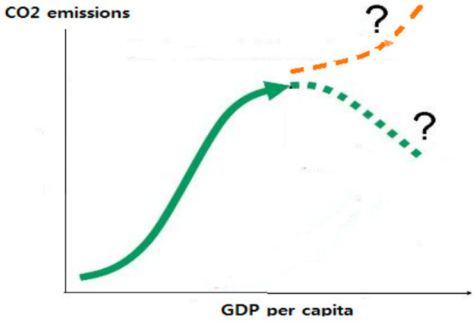

Fig. 4. Potential Extensions of EKC with N-shaped or Open-ended Trajectories

(Source: Munasinghe, M. (1999))

For trade openness, the models anticipate that the coefficient of the trade openness variable (β3 or β4 depending on the model) will be positive in the initial stages, implying that free trade increases CO2 emissions due to the expansion of economic activities. This aligns with the "pollution haven hypothesis" in some contexts. However, it is also possible that the relationship is more complex, and at higher levels of trade openness, CO2 emissions may decrease due to the

transfer of clean technologies and improved environmental standards, potentially reflecting a "pollution halo" effect. This potential for a non-linear relationship with trade openness could be further explored by including a squared term for trade openness, similar to the treatment of GDP.

The objective of this analysis is to test the existence of the EKC, evaluate the role of trade openness in influencing CO2 emissions, and analyze the variations in CO2 emissions over time and across Southeast Asian countries. The results of the models will provide critical insights into how GDP, trade, and other related factors impact CO2 emissions in the region during the study period from 1990 to 2022.

3.2 Research Implementation Process

The study employs a methodical approach to ensure that the results are comprehensive and reliable. We obtained our data from reputable sources such as the World Bank, examining critical variables including GDP per capita, CO2 emissions, and economic openness. A comprehensive cleaning procedure was employed to prepare the data for analysis. This involved imputing absent values and ensuring the consistency of all datasets. We created additional variables, such as per capita CO2 emissions and logarithmic conversions of GDP, to facilitate statistical analysis.

The study employed quadratic and cubic regression models to assess the Environmental Kuznets Curve (EKC) hypothesis. Carbon dioxide emissions served as the dependent variable, while trade openness and gross domestic product per capita functioned as the independent variables. The models aimed to determine the point at which economic expansion transitions from worsening to mitigating environmental deterioration by analyzing the non-linear relationships among these factors. We examined the influence of trade openness to determine its effect on the strength of this link. The results were evaluated based on statistical significance, regression coefficients, and the explanatory power of the models. Turning points were determined to identify the income level at which CO2 emissions begin to decline. This facilitated comprehension of the EKC hypothesis. The statistics were analyzed within the context of each Southeast Asian nation, highlighting their parallels and differences. This method elucidated the intricate link among trade liberalization, economic growth, and environmental sustainability. It served as the foundation for evidence-based policy recommendations.

3.3 Data souce and variable

The dataset comprises annual time series data for eight Southeast Asian nations: Brunei Darussalam, Cambodia, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. The objective is to employ this data for time series regression analysis. The data encompasses the period from 1990 to 2022 and incorporates significant variables such as trade openness, GDP, and CO2 emissions. The 33-year span (1990–2022) is sufficient to analyze long-term trends and patterns in the time series, facilitating more precise findings. This period encompasses significant occurrences in Southeast Asia, such as the Asian Financial Crisis of 1997–1998 and the ASEAN integration process, culminating in the establishment of the ASEAN Economic Community (AEC).

Table 4. Key Variables, Definitions, and Measurements

No.	Variable	Definition	Measurement	Source
1	GDP (constant 2015 US$)	The total value of goods and services produced in a country, adjusted for inflation, to reflect real economic strength over time.	Constant 2015 US dollars	WDI
2	Carbon dioxide (CO2) emissions (total) excluding LULUCF (Mt CO2e)	CO2 emissions generated from industrial and energy-related activities, excluding emissions from land use, land-use change, and forestry (LULUCF)	Million metric tons of CO2 equivalent	WDI
3	Carbon dioxide (CO2) emissions excluding LULUCF per capita (t CO2e/capita)	Average emissions of CO2 per person, excluding contributions from LULUCF.	Metric tons of CO2 equivalent per capita	WDI
4	The degree of openness	An indicator of how open a country's economy is to international trade.	The ratio of total trade (exports + imports) to GDP (%)	WDI
5	Population	The total number of individuals residing within a country in a given year.	Total population (number of people)	WDI

(Author's Synthesis)

CO2 emissions, measured in metric tons, were converted to per capita emissions to account for population size in each country, ensuring consistent comparisons. GDP was calculated based on real GDP per capita, using data adjusted to constant 2015 US dollars (constant US$ 2015) to eliminate the effects of inflation and price fluctuations. Trade openness, representing the level of global economic integration, was measured as the ratio of total exports and imports to annual GDP. Standardizing the data in constant values and per capita terms ensures accuracy and transparency in analyzing the relationship between economic development, trade liberalization, and CO2 emissions across Southeast Asian countries. In subsequent analyses, the data will be transformed into natural logarithmic (ln) form to facilitate regression methods and improve interpretability of the coefficients.

Table 5. Descriptive Statistics of GDP, Economic Openness, and CO2 Emissions in Southeast Asian Countries

Country	GDP per Person Mean	GDP per Person Std. Dev	Openness Mean	Openness Std. Dev	CO2 per person Mean	CO2 per person Std. Dev	CO2 metric tons Mean	CO2 metric tons Std. Dev
Viet Nam	1,835.62	874.66	94.22%	53.56%	1.48	1.00	132.64	102.35
Thailand	4,559.86	1,166.42	107.12%	21.33%	3.25	0.65	215.70	57.34
Malaysia	7,637.42	2,011.32	139.59%	16.65%	6.33	1.48	173.67	67.96
Singapore	43,484.68	13,270.01	293.67%	51.57%	10.24	0.85	46.04	6.91
Philippines	2,312.23	647.57	56.19%	8.70%	0.97	0.19	88.84	31.76
Indonesia	2,520.35	793.07	41.59%	5.10%	1.63	0.43	392.35	147.46
Cambodia	1,094.81	503.74	83.09%	34.32%	0.36	0.31	5.48	5.36
Brunei Darussalam	35,440.23	4,497.75	93.63%	13.51%	17.03	2.53	6.28	1.79

(Author's Synthesis)

Singapore leads with an average GDP per capita of $43,484, reflecting its position as a global financial hub and a highly developed economy. Meanwhile, Cambodia has the lowest GDP per capita, at only $1,094, highlighting its status as a developing country. The high standard deviation in GDP for countries like Indonesia and Malaysia indicates significant economic scale fluctuations during the studied period.

Singapore outperforms other nations in GDP per capita due to its focus on high-tech industries and financial services. In contrast, Cambodia and Vietnam remain heavily reliant on agriculture and traditional industries. Singapore also boasts the highest average trade openness (2.396), demonstrating its deep integration into global markets. Conversely, Indonesia and the Philippines have lower levels of openness, at 0.415 and 0.561 respectively, reflecting a stronger focus on domestic markets or lower levels of international integration.

In terms of per capita CO2 emissions, Brunei leads with 17 tons per person, primarily due to its reliance on the oil and gas industry. Meanwhile, Cambodia has the lowest CO2 emissions, thanks to its less industrialized economy and predominant use of traditional energy sources. For total CO2 emissions, Malaysia and Thailand have the highest average total emissions (173,671 and 215,699 tons, respectively), reflecting their high levels of industrialization and significant energy consumption. In contrast, Singapore, despite its high GDP per capita, has much lower total emissions (46,041 tons) due to stringent environmental policies and the adoption of clean technologies.

4. RESULTS AND DISCUSSION

4.1 Background of Southeast Asian Countries

Based on the total GDP and total CO2 emissions of Southeast Asian countries, the results clearly demonstrate a strong relationship between economic growth and CO2 emissions:

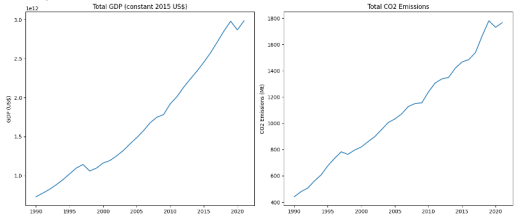

Fig. 5. Total GDP and Total CO2 Emissions in Southeast Asia (1990-2022)

(Author's Synthesis)

The combined GDP of Southeast Asian countries has followed a steady upward trajectory from 1990 to 2020, with especially rapid growth from the early 2000s onward. This expansion was largely fueled by industrialization, services, and trade. Yet, economic progress came hand in hand with rising CO_2 emissions, highlighting a strong connection between growth and environmental impact, a pattern that resonates with the Environmental Kuznets Curve (EKC) findings in the region.

Throughout the same period, CO_2 emissions rose consistently, largely due to the region's reliance on fossil fuels such as coal, oil, and natural gas to power production and meet energy needs. However, the pace of emissions growth did not always match the speed of GDP growth. At certain times, economies grew faster than emissions, suggesting a partial

decoupling. This shift points to the influence of cleaner energy choices and environmental policies that have started to slow down the carbon intensity of growth.

Both GDP and emissions also reflected the turbulence of global economic downturns. During the Asian Financial Crisis in the late 1990s and the Global Financial Crisis of 2008, GDP growth slowed noticeably, and emissions growth also dipped. Even so, CO_2 emissions rarely declined outright; they typically kept rising, though at a slower pace. This persistence underlines the complexity of the growth, emissions relationship and suggests that deeper structural changes in energy systems and production are needed if Southeast Asia is to achieve lasting reductions in emissions while continuing to grow.

4.1.1 High income: Singapore, Brunei

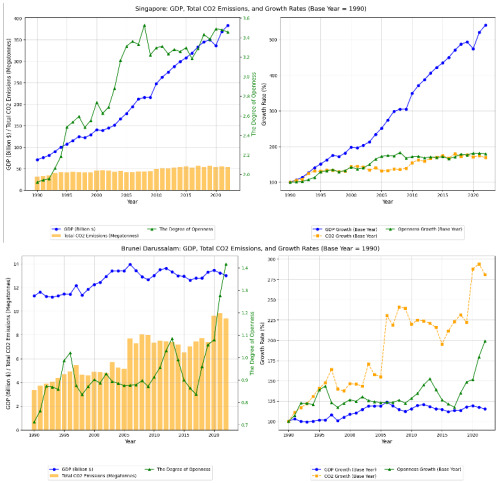

Fig. 6. Singapore, Brunei: GDP, Total CO2 Emissions, and Growth Rates

(Author's Synthesis)

Singapore and Brunei Darussalam are both classified as high-income economies in Southeast Asia, yet their development trajectories and environmental outcomes diverge sharply. While both remain heavily reliant on external drivers—Singapore on global trade and services, and Brunei on oil and gas exports—the ways in which they manage the balance between growth and sustainability are markedly different.

Singapore exemplifies effective national structural transformation. Over several decades, the economy transitioned from a manufacturing-based model to one more reliant on knowledge, services, and advanced technology. This strategic alteration not only maintained constant GDP growth but also contributed to a gradual reduction in CO_2 emissions, ultimately leading to a decline post-2011. Proactive and forward-thinking policies, including early investment in clean technologies, consistent promotion of energy efficiency, and trade agreements adhering to environmental norms, facilitated these outcomes. Singapore's trajectory demonstrates that economies largely dependent on trade can prevent emissions from escalating by including sustainability into their long-term planning and governance frameworks.

Brunei, by contrast, has remained heavily reliant on oil and gas revenues, which has limited diversification and left the economy exposed to global energy price volatility. As a result, GDP growth has been modest and unstable, while CO_2 emissions have remained consistently high. Attempts to expand into tourism and renewable energy have achieved only limited results, and the overall pace of transition toward sustainability has been slow. The cyclical nature of this dependence is evident: when oil prices recover, both trade openness and emissions rise, underscoring the structural constraints of a resource-based growth model.

This comparison underscores a critical lesson for Southeast Asia. Singapore illustrates the possibility of decoupling economic growth from emissions by diversifying its economic base and embedding sustainability within policy frameworks. Brunei, however, highlights the challenges faced by resource-dependent economies when diversification is delayed or insufficient. Together, these cases suggest that sustainable growth in the region depends on decisive structural transitions toward innovation, energy efficiency, and low-carbon development models.

4.1.2 Upper-middle income: Malaysia, Thailand

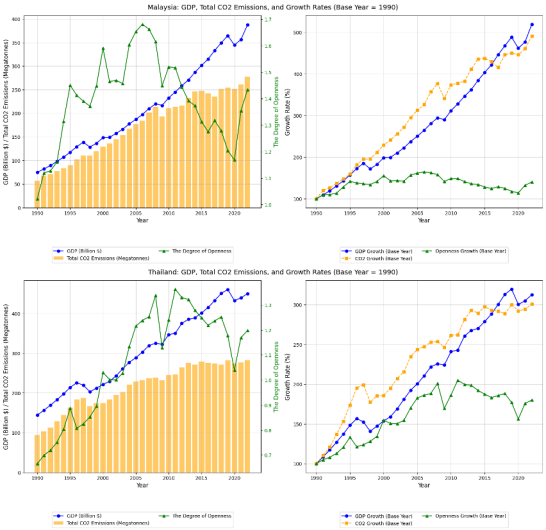

Fig. 7. Malaysia, Thailand: GDP, Total CO2 Emissions, and Growth Rates

(Author's Synthesis)

Malaysia and Thailand are among the most vibrant rising economies in Southeast Asia. In the last 30 years, both have experienced swift industrialization, significant integration into global trade, and increasing energy consumption. Their economic trajectories indicate that they encounter analogous challenges: robust GDP growth coupled with escalating CO_2 emissions, signifying their continued reliance on fossil fuels and energy-intensive industries. The two situations differ due to their resilience levels, diversification tactics, and responses to environmental policies. An export-oriented industrialization strategy has significantly influenced Malaysia's growth. Since the early 1990s, the nation has diligently endeavored to rapidly expand its economy through the exportation of heavy industries, electronics, and palm oil. This has facilitated GDP growth and enhanced trade openness. This policy accelerated Malaysia's incorporation into global value chains; however, it also resulted in significant CO_2 emissions due to the country's continued dependence on oil and natural gas.

The Asian Financial Crisis (1997–1998) temporarily halted growth, resulting in a reduction of emissions and trade. However, Malaysia swiftly recovered due to banking reforms and incentives for foreign investment. Commencing in the 2000s, the economy expanded concurrently with rising emissions, and the continuous execution of substantial infrastructure projects. Efforts to encourage renewable energy have intensified since 2015, particularly through initiatives such as the Malaysia Energy Transition Plan and pledges under the Paris Agreement. Nonetheless, these endeavors have yet to yield significant results. Malaysia's situation exemplifies a tension between a robust economy and a sluggish rate of decarbonization.

Thailand's trajectory of prosperity parallels that of other nations that have industrialized via exports, however it possesses distinct characteristics. During the 1990s, substantial growth occurred due to foreign direct investment (FDI) and export-oriented sectors. Simultaneously, CO_2 emissions increased. The Asian Financial Crisis adversely affected Thailand to a greater extent than Malaysia. It resulted in a significant decline in GDP and a temporary reduction in emissions. Thailand's economy progressively enhanced in the 2000s as it diversified into high-tech sectors and high-value agriculture, while maintaining strong ties to global trade. Despite the economy's diversification, CO_2 emissions continued to rise, indicating a persistent reliance on energy-intensive sectors. The pandemic of 2020–2021 severely impacted Thailand's economy, particularly due to the collapse of tourism, a significant component of GDP. This resulted in a decline in both trade openness and emissions. Thailand has lagged behind Malaysia in implementing comprehensive energy transition legislation, rendering the nation more susceptible to the coupling of emissions growth. Southeast Asian emerging economies, like as Malaysia and Thailand, have the dilemma of balancing growth with emissions. Malaysia has leveraged its natural resources and manufacturing capabilities to emerge as a significant exporter in the area; yet, this has also resulted in elevated pollution levels. Thailand's economy exhibits greater diversity due to its reliance on foreign direct investment and tourism; nonetheless, reducing emissions intensity remains as challenging.

Malaysia has demonstrated more proactive governmental commitments to renewable energy in recent years, but Thailand has seen less advancement in environmental governance. In all instances, the primary issue remains consistent: to decouple economic growth from CO_2 emissions, it is imperative to diversify energy sources, enhance their efficiency,

and increase investments in environmentally beneficial technologies. Their experiences underscore the regional imperative of balancing global commercial competitiveness with long-term environmental sustainability.

4.1.3 Lower-middle income: Vietnam, Philippines, Indonesia, Cambodia

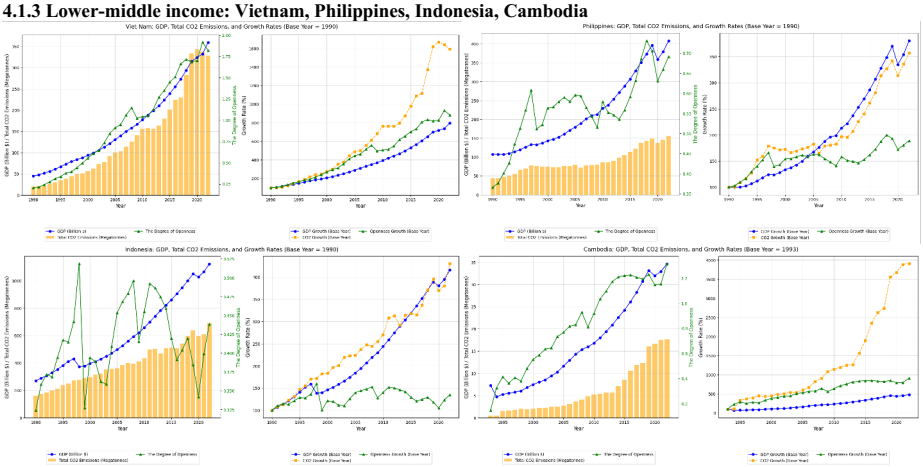

Fig. 8. Vietnam, Philippines, Indonesia, Cambodia: GDP, Total CO2 Emissions, and Growth Rate

(Author's Synthesis)

Vietnam, Indonesia, the Philippines, and Cambodia are lower-middle-income nations that have had significant economic growth since the 1990s. This expansion has been driven by industrialization, regional integration, and increasing trade. Despite this progress, CO_2 emissions have consistently increased, demonstrating a significant correlation between growth and emissions. This indicates that these economies remain in the pre-EKC phase, when persistent decoupling has not yet occurred.

Trade openness generally increased, though with varying intensity: Vietnam and Cambodia integrated most visibly, Indonesia's openness fluctuated with commodity cycles, and the Philippines trended upward more moderately. Across the group, energy systems remain heavily fossil-dependent, meaning that efficiency gains and early renewable adoption have not offset rising demand. External shocks such as the Asian Financial Crisis (1997–1998), the Global Financial Crisis (2008), and the COVID-19 pandemic (2020) produced only temporary dips in emissions, which quickly rebounded during recovery phases.

Vietnam has seen significant transformation since the Đổi Mới reforms, emerging as one of the most remarkable developments in Southeast Asia. Membership in ASEAN, the WTO, and bilateral trade agreements has resulted in consistent GDP growth and a significant enhancement in trade openness. This trajectory has resulted in a significant increase in CO_2 emissions, primarily due to export-oriented industries and the reliance on fossil fuels for energy. The government has implemented regulations for renewable energy and efficiency; yet, the primary challenge is decoupling growth from emissions while maintaining competitive exports.

Indonesia's trajectory illustrates the tension between dependence on natural resources and the pursuit of sustainability. The exportation of coal, oil, gas, and palm oil has significantly accelerated economic growth; yet, emissions have concurrently increased at a comparable rate. Trade openness has fluctuated with commodity cycles, however emissions have remained elevated due to the nation's dependence on fossil fuels. In recent years, there has been an increased emphasis on advancing renewable energy and enhancing energy efficiency. Nonetheless, dependence on coal continues to impede the transition to a more sustainable energy system. Indonesia exemplifies the challenges of sustaining economic momentum while transitioning from resource-dependent growth patterns.

The Philippines possesses a diverse economy, characterized by robust expansion in services, particularly in business process outsourcing (BPO), alongside manufacturing and infrastructure development. Since the 2000s, GDP growth has been robust; yet, trade openness has expanded at a slower rate compared to other nations in the region. Nonetheless, CO_2 emissions have continued to rise due to ongoing energy-intensive industrialization. Renewable energy policies have been implemented; yet, they are insufficient to halt the escalating prices. The Philippines exemplifies the challenge of reconciling a burgeoning services economy with persistent emissions from traditional sectors.

Cambodia's trajectory illustrates both the opportunities and the risks associated with rapid development from a modest baseline. The economy has transitioned from agriculture to textiles, construction, and tourism. This has resulted in accelerated GDP growth and increased trade openness. Initially, CO_2 emissions were little; however, they have significantly increased since that time. The growth rate has diminished slightly in recent years. Environmental policies remain nascent, and in the absence of more robust sustainability standards, the ecological consequences of

industrialization may escalate. Cambodia exemplifies a nation in need of development, however it lacks robust sustainability frameworks.

The four nations illustrate the trade-off between economic expansion and emissions typical of lower-middle-income economies. Vietnam and Indonesia have the most robust correlation between GDP and emissions. Cambodia exhibits the most rapid relative emissions rise from a minimal baseline, while the Philippines demonstrates the advantages of a diversified economy yet continues to grapple with increasing energy consumption. Trade openness has significantly contributed to growth; yet, its environmental impacts have varied: it evidently heightened emissions in Vietnam and Cambodia, exhibited greater volatility in Indonesia, and had a moderate influence in the Philippines. The shared challenge for all four economies is to accelerate energy transition, improve efficiency, and embed sustainability into trade and investment strategies in order to bend the emissions curve while sustaining economic dynamism.

4.2 Empirical Results

To estimate and quantify the effects of trade liberalization on income and environmental quality, it is essential to approach this as an empirical problem, as the outcomes vary depending on factors such as a country's development stage, degree of openness, population, and specific policies. This paper considers exogenous variables such as GDP, trade openness (OPEN), and other environmental and development indicators. By performing Ordinary Least Squares (OLS) estimation for individual countries, we can assess the impact on each country's environment. Separate country regressions allow for heterogeneous effects, reflecting differences in the development levels of the countries within the sample.

To investigate the relationships between environmental degradation, economic growth, and trade liberalization, we employ simple OLS regression analysis. The tables below present the regression results for each country based on two model specifications: one including the quadratic term of GDP and the other incorporating the cubic term of GDP. Since the two models differ by only one parameter, a t-test is used to determine which model is more appropriate.

The primary focus of the analysis is on the estimated coefficients, their signs, and statistical significance. The study considers both quadratic (Model 1) and cubic (Model 2) specifications to identify the potential presence or absence of the Environmental Kuznets Curve (EKC), whether it follows an inverted U-shape or N-shaped pattern.

Table 6. Results from OLS estimation method (Singapore, Brunei)

	Singapore		Brunei Darussalam	
	Model 1	Model 2	Model 1	Model 2
Constant	2.94	-1296.06***	-238.82	-15737.00
ln(GDP)	-0.32	364.59***	46.69	4480.38
ln(GDP)^2	0.02	-34.10***	-2.25440	-425.01
ln(GDP)^3	-	1.06***	-	13.44
Openness	0.60296	-0.29	-0.38	-0.46
Openness^2	-0.14121*	0.009	0.34	0.42
R-squared	0.686	0.77	0.46	0.48
F-value	15.29	17.76	5.97	5.04
DW-statistics	1.52	1.77	1.22	1.36

(Author's Synthesis)

For Brunei Darussalam, neither the quadratic (Model 1) nor the cubic (Model 2) specification provides statistically significant support for the EKC hypothesis. In Model 1, the positive coefficient of ln(GDP) and the negative coefficient of ln(GDP)² suggest the theoretical possibility of an inverted U-shape, but both coefficients are statistically insignificant ($p = 0.222$ and $p = 0.218$, respectively). Likewise, in Model 2, none of the GDP-related terms (ln(GDP), ln(GDP)², ln(GDP)³) reach statistical significance, with p-values around 0.28. The variables representing trade openness and its squared term are also consistently insignificant across both models (p-values between 0.64 and 0.85). Although the Durbin–Watson statistics (1.22 and 1.36) are not alarmingly low, they do suggest some degree of positive autocorrelation. Overall, these results indicate that neither model adequately captures the relationship between GDP, trade openness, and CO_2 emissions in Brunei Darussalam. This outcome may reflect the country's unique economic structure—highly dependent on oil and gas exports with limited diversification—underscoring the need for alternative model specifications or the inclusion of additional explanatory variables to better explain emissions dynamics.

Singapore

In Singapore's case, Model 1 (quadratic) fails to confirm the EKC hypothesis, as neither the negative coefficient of ln(GDP) nor the positive coefficient of ln(GDP)² is statistically significant ($p \approx 0.96$ and 0.95, respectively). By contrast, Model 2 (cubic) yields a more compelling result: all three GDP terms (ln(GDP), ln(GDP)², ln(GDP)³) are highly significant ($p \approx 0.005$), and their signs (+, –, +) are consistent with an N-shaped EKC. This pattern suggests that CO_2 emissions may first rise, then decline, and eventually rise again at higher income levels—reflecting the possibility of re-emerging environmental pressures as the economy advances. While trade openness and its squared term remain statistically insignificant in both models, the overall fit of Model 2 is stronger ($R^2 = 0.767$; $F = 17.76$), and the Durbin–

Watson statistic of 1.77 indicates fewer concerns about autocorrelation compared to Brunei and several other countries in the dataset. Taken together, these results suggest that Singapore exhibits evidence of a more complex, nonlinear emissions–growth relationship, with Model 2 providing a more robust representation than the quadratic specification.

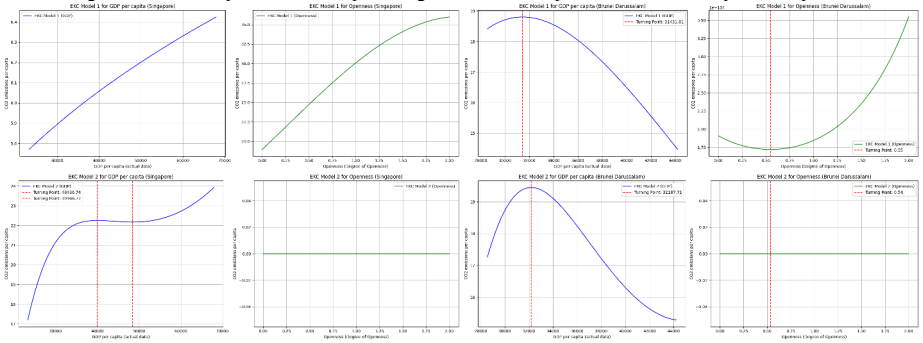

Fig. 9. EKC Model 1&2 (Singapore, Brunei)

(Author's Synthesis)

In Model 1 (quadratic), the GDP–CO_2 relationship shows a steady upward trend with no turning point, and trade openness also follows a linear positive path, consistent with the lack of statistical significance. By contrast, Model 2 (cubic) reveals an N-shaped EKC with two turning points (≈39,967 and 48,437), confirming the regression results where all GDP terms are significant. However, trade openness remains flat, indicating little explanatory power in either model. Overall, Model 2 better captures Singapore's complex GDP–CO_2 dynamics, though the role of openness remains unclear.

Brunei Darussalam

For Brunei, Model 1 suggests an inverted U-shaped EKC with a GDP turning point around 31,432, while trade openness shows a U-shaped curve with a turning point near 0.55. Model 2 produces a similar inverted U-shape with a slightly higher turning point (≈32,188), but trade openness again appears flat and insignificant. Although the graphs imply potential non-linear effects of GDP and openness, the weak statistical support limits the reliability of these interpretations.

Table 7. Results from OLS estimation method (Thailand and Malaysia)

Country	Thailand		Malaysia	
	Model 1	Model 2	Model 1	Model 2
Constant	-81.91***	-353.38	-69.96***	1043.08***
ln(GDP)	18.98***	116.92	15.61***	-360.90***
ln(GDP)^2	-1.09***	-12.85	-0.83***	41.55***
ln(GDP)^3	-	0.47	-	-1.59***
Openness	0.87	0.69	-2.47**	-0.55
Openness^2	-0.41	-0.31	0.94***	0.28
R-squared	0.98	0.98	0.97	0.98
F-value	283.68	223.28	213.26	229.71
DW-statistics	0.73	0.71	0.95	1.31

(Author's Synthesis)

For Thailand, the quadratic model (Model 1) provides strong evidence of an inverted U-shaped EKC. Both ln(GDP) and $\ln(GDP)^2$ are highly significant with the expected signs, confirming that emissions rise with income up to a turning point before declining. In contrast, the cubic model (Model 2) adds no explanatory value, as the cubic term is insignificant. Trade openness shows a non-linear effect on emissions in both models, but very low Durbin–Watson values (≈0.7) point to autocorrelation. Overall, Model 1 offers the clearest support for the EKC in Thailand, though autocorrelation should be addressed.

In Malaysia, Model 1 also suggests an inverted U-shape, with GDP and GDP^2 both significant and correctly signed. Model 2, however, introduces a negative and significant cubic term, which contradicts the expected N-shaped EKC and complicates interpretation. Trade openness appears non-linear in Model 1, but only the squared term is significant in Model 2. The Durbin–Watson statistic improves in Model 2 (1.31 vs. 0.95), suggesting less autocorrelation, yet the anomalous cubic sign weakens its validity. Thus, while both models show some EKC evidence, Model 1 is more

consistent with theory.

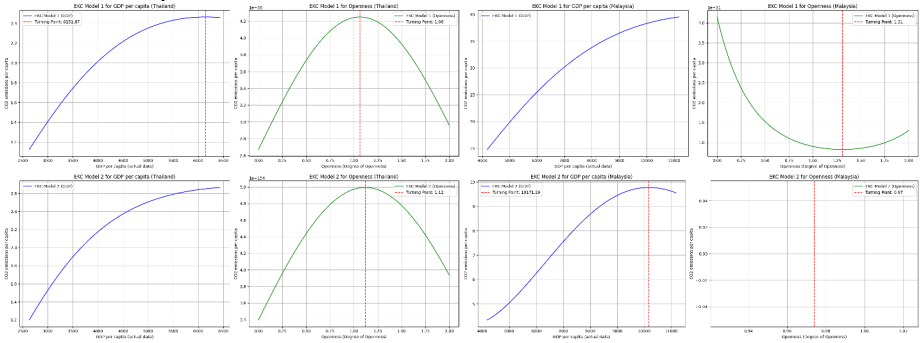

Fig. 10. EKC Model 1&2 (Thailand, Malaysia)

(Author's Synthesis)

The graphs from Model 1 (quadratic) clearly show an inverted U-shape for both GDP per capita and trade openness, with turning points around 6,152 and 1.06, respectively. This supports the EKC hypothesis and matches the regression results. Model 2 (cubic) produces similar shapes, but since the cubic GDP term is not significant, it adds little explanatory value. Overall, the quadratic model provides the most reliable evidence for Thailand's EKC.

For Malaysia, Model 1 illustrates an inverted U-shape for GDP per capita with a turning point at about 10,171, consistent with the EKC. Trade openness also shows a non-linear effect, bottoming at 1.31. In Model 2, GDP still follows a non-linear path, but the negative cubic term complicates interpretation, and openness exhibits little variation. Thus, the quadratic model offers clearer and more interpretable support for the EKC in Malaysia.

Table 8. Results from OLS estimation method (Viet Nam, Philippines, Indonesia, Cambodia)

	Viet Nam		Philippines		Indonesia		Cambodia	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Constant	-18.45**	-75.93	102.52***	577.76	-57.23***	-1111.09***	66.66***	215.18
ln(GDP)	3.54*	28.06	-27.37***	-211.24	14.38***	420.70***	-21.32***	-86.01
ln(GDP)^2	-0.14	-3.61	1.78***	25.49	-0.86***	-52.99***	1.62***	10.97
ln(GDP)^3	-	0.16	-	-1.02	-	2.23***	-	-0.45
Openness	0.10	0.47	7.45***	7.15***	-9.204*	-13.89***	4.46***	4.61***
Openness^2	-0.03	-0.17	-5.85***	-5.44***	10.66*	16.29***	-2.27***	-2.44***
R-squared	0.99	0.99	0.93	0.93	0.93	0.95	0.96	0.96
F-value	1243.38	981.22	94.79	74.93	86.91	104.63	134.37	105.44
DW-statistics	0.9	1	0.97	0.96	0.61	0.84	1.96	2.05

(Author's Synthesis)

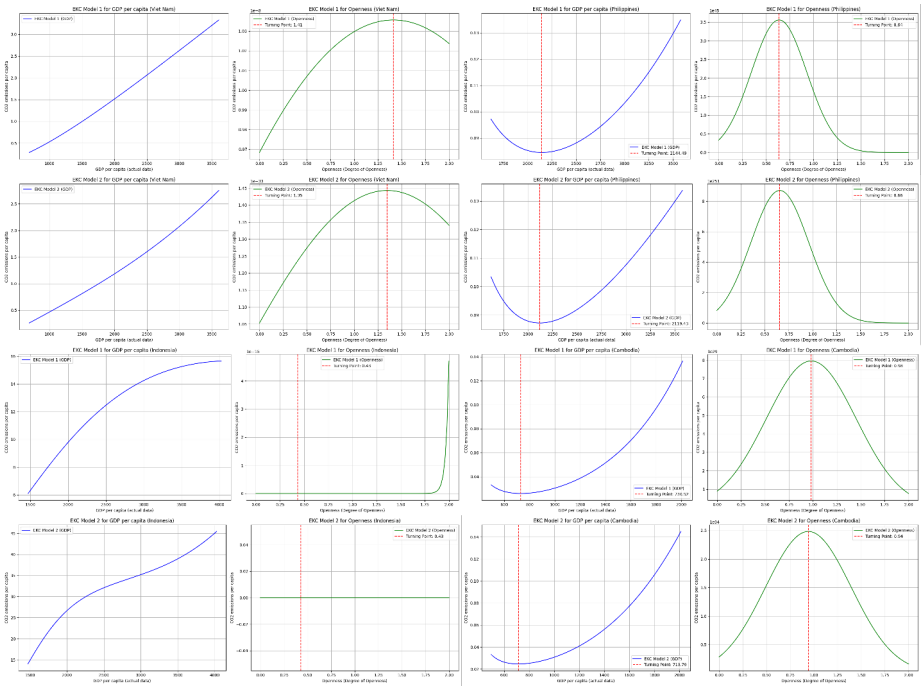

Fig. 11. EKC Model 1&2 (Vietnam, Philippines, Indonesia, Cambodia)

(Author's Synthesis)

Across the four lower-middle-income countries, the econometric analysis reveals diverse patterns in the GDP–emissions relationship. For Vietnam, neither the quadratic nor cubic specification provides statistically significant support for the EKC. High p-values and low Durbin–Watson statistics point to weak results and potential autocorrelation, leaving no reliable evidence of an inverted U-shape. In the Philippines, Model 1 produces strong statistical significance but suggests a U-shaped curve, where emissions decline at lower income levels and rise again with further growth, contradicting the EKC. Trade openness shows a significant non-linear effect in both models, although autocorrelation remains a concern and the cubic term adds little explanatory value. Indonesia presents more complex dynamics: while the quadratic model supports an inverted U-shape, the cubic model indicates an N-shaped EKC with all GDP terms significant and trade openness also influential. However, very low DW statistics weaken the robustness of these findings. Cambodia stands out as the strongest case, with Model 1 confirming a textbook inverted U-shaped EKC supported by highly significant GDP and GDP² coefficients, along with a meaningful non-linear role for trade openness. Importantly, DW values close to 2 suggest little to no autocorrelation, making Model 1 the most reliable specification. Taken together, these results highlight marked contrasts: Vietnam provides no evidence for the EKC, the Philippines follows an unconventional U-shaped path, Indonesia suggests a complex N-shape, and Cambodia strongly supports the EKC hypothesis.

The graphical evidence reinforces these conclusions. For Vietnam, GDP–CO_2 curves rise monotonically with no turning point, while trade openness shows only weak hump-shaped effects with turning points around 1.25–1.45. In the Philippines, the GDP graphs depict a clear U-shape, while trade openness exhibits an inverted U-curve peaking near 0.64, suggesting that integration initially worsens but later alleviates emissions. Indonesia's GDP–emissions relationship appears as an inverted U-shape in the quadratic model and an N-shape in the cubic specification, though the openness curves remain largely flat, indicating limited influence. Cambodia again provides the clearest case, with GDP following a distinct inverted U-shape and trade openness showing a hump-shaped pattern peaking around 0.85, both consistent with the regression outcomes. Collectively, the visual evidence confirms the econometric results: Cambodia strongly supports the EKC, Vietnam shows no evidence, the Philippines follows a non-standard U-shape, and Indonesia displays a complex non-linear path.

Turning to Brunei Darussalam, the evidence tentatively supports the EKC for GDP per capita, but the role of trade openness remains less clear. The U-shaped relationship observed in Model 1 for trade openness suggests that greater

integration may initially improve environmental outcomes, but beyond a threshold (around 0.55), further openness could exacerbate emissions. This underlines the importance of considering structural economic factors and policy design in interpreting the EKC across small resource-dependent economies.

4.3 Overview of EKC Threshold Effects

The results indicate significant differences among the analyzed countries regarding the existence, shape, and turning points of the EKC. These differences reflect the diversity in economic structures, environmental policies, and stages of development. Six countries, Thailand, Malaysia, Singapore, the Philippines, Indonesia, and Cambodia, exhibit evidence of EKC threshold effects, confirming an inverted U-shaped relationship between economic growth and environmental degradation.

Table 6: Summary of EKC Threshold Effects

	Viet Nam	**Thailand**	**Malaysia**	**Singapore**	**Philippines**	**Indonesia**	**Cambodia**	**Brunei Darussalam**
The existence of threshold effect	No	Yes	Yes	Yes	Yes	Yes	Yes	No
Quadratic/Cubic effect	-	Quadratic	Cubic	Cubic	Quadratic	Cubic	Quadratic	-

Thailand, the Philippines, and Cambodia exhibit quadratic relationships characterized by a singular turning point, facilitating comprehension. This indicates that these nations have attained a level where environmental policies and public awareness are sufficiently robust to halt the trend of increasing pollution associated with economic expansion. Conversely, Malaysia, Singapore, and Indonesia exhibit more intricate cubic relationships characterized by two inflection points. This indicates that pollution levels temporarily increase before the ecosystem undergoes a lasting improvement. Conversely, Vietnam and Brunei Darussalam do not exhibit distinct threshold effects. This is likely due to their divergent economic priorities or distinct structural challenges. Thailand, the Philippines, and Cambodia demonstrate more direct quadratic correlations defined by a single turning point. This indicates that these nations have attained a level where environmental policies and public awareness are sufficiently robust to halt the trend of increasing pollution associated with economic expansion. Conversely, Malaysia, Singapore, and Indonesia exhibit more intricate cubic relationships characterized by two inflection points. This indicates that pollution levels temporarily increase before the ecosystem undergoes a lasting improvement. Conversely, Vietnam and Brunei Darussalam do not exhibit distinct threshold effects. This is likely due to their economies concentrating on disparate factors or possessing distinct structural issues.

4.4 Countries Exhibiting EKC Threshold Effects

Thailand exhibits a clear quadratic relationship with a turning point at approximately $6,151.87, confirming an inverted U-shaped EKC in which pollution initially rises with GDP growth but eventually declines. The National Economic and Social Development Plan (NESDP) of the country encompasses many policies aimed at advancing renewable energy, mitigating air and water pollution, and overseeing waste management. Thailand has invested significantly in solar, wind, and biomass initiatives. It has established stringent emission limits and promoted the segregation of waste, recycling, and the utilization of modern treatment technology to reduce reliance on landfills.

Malaysia, by contrast, displays a cubic EKC with turning points at $10,171.29 and $11,065.80, highlighting challenges linked to economic restructuring. The Environmental Quality Act of 1974 provides the legal foundation for pollution control, while the National Environmental Policy focuses on sustainable resource use and pollution reduction. Malaysia further promotes green technology adoption through financial incentives and tax exemptions, reflecting its commitment to balancing growth with environmental protection.

Singapore also presents a cubic EKC, with turning points at $48,436.74 and $59,965.77. Despite its rapid industrialization, the country has successfully embedded sustainability into policy through the Singapore Green Plan 2030, which sets targets for sustainable urban growth and environmental management. Singapore has advanced waste management systems such as recycling and waste-to-energy programs, while also investing heavily in clean energy, air quality improvements, and wastewater treatment research, underscoring its proactive approach to sustainability.

The Philippines demonstrates an inverted U-shaped EKC with a turning point at $2,144.49, reflecting the influence of strong environmental laws, including the Philippine Clean Air Act (RA 8749) and the Ecological Solid Waste Management Act (RA 9003). Complementary watershed management programs have also helped to reduce environmental degradation and preserve ecosystems, supporting progress toward sustainability.

Indonesia, meanwhile, follows a cubic EKC with turning points at $3,218.71 and $4,378.20, indicating temporary increases in pollution during industrialization and urbanization phases before eventual reductions. Its environmental governance is anchored in the Environmental Protection and Management Act (Law No. 32/2009), complemented by climate change mitigation measures and sustainable forestry programs to address deforestation and biodiversity loss.

Finally, Cambodia displays a quadratic EKC with a turning point at $730.52. Environmental progress there is guided by the Law on Environmental Protection and Natural Resource Management and supported by the Climate Change Strategy and Action Plans, which outline specific measures to mitigate risks while promoting green growth.

4.5 Countries Without Clear EKC Threshold Effects

Vietnam does not provide statistical evidence of an Environmental Kuznets Curve threshold effect. This outcome may be associated with its developmental trajectory propelled by industrialization and the comparatively lax implementation of environmental regulations. To align economic growth with sustainability objectives, it is essential to enhance the institutional structure, facilitate the dissemination of cleaner technology, and elevate knowledge of environmental concerns.

Vietnam's deviation from the EKC can be explained by its export-driven industrialization, which depends on fossil fuels and has limited implementation of emission standards. Brunei's reliance on oil and gas for its resources is what keeps its emissions high even though it has higher income. These patterns show that structural dependence to some extend is more important than policy failure.

Brunei Darussalam lacks distinct Environmental Kuznets Curve impacts, perhaps due to its reliance on oil and gas for economic sustenance. This unconventional approach to business may not align with the standard EKC model. Further research is necessary to explore alternative frameworks that more efficiently support resource-dependent economies.

ASEAN's regional strategies, like the ASEAN Plan of Action for Energy Cooperation (APAEC 2016–2025), are meant to improve the use of renewable energy, but progress is still slow. The results indicate that regional coordination can be improved by establishing shared carbon markets and facilitating technology transfers.

5. CONCLUSION

The research indicates a robust correlation between economic expansion and increasing CO_2 emissions in eight Southeast Asian nations. The swift industrialization in Malaysia, Thailand, and Indonesia has heightened energy demand, hence causing significant increases in emissions. The Environmental Kuznets Curve (EKC) offers restricted explanatory power. Certain nations conform to the expected inverted U-shaped trend, while others deviate, suggesting that the relationship between growth and environmental quality is more complex and context-specific than a singular model can encompass.

Trade openness serves a dual function. In certain instances, international integration has resulted in the adoption of cleaner technologies and more stringent environmental regulations. In certain instances, it has augmented emissions contingent upon the energy infrastructures, industries, and policies of individual nations. The findings indicate that Southeast Asian nations must prioritize sustainability in their growth strategies immediately. To ensure that future economic growth does not adversely affect the environment, it is imperative to enhance the accessibility of renewable energy, optimize efficiency across all sectors, and promote responsible consumption.

5.1 Implication

The findings have significant implications for both researchers and policymakers. The research highlights the imperative for Southeast Asian policymakers to integrate environmental goals into economic growth policies. A definitive correlation exists between accelerated growth and increasing CO_2 emissions; however, the varying outcomes among countries indicate that effective policies can alter this trajectory. To achieve equilibrium between growth and sustainability, it is imperative to increase investment in renewable energy, enhance energy efficiency, and enforce more stringent environmental regulations. Trade liberalization may enhance standards and foster technological advancements; but, it might perpetuate carbon-intensive practices in the absence of effective regulations. This underscores the significance of formulating trade and industrial policies that promote low-carbon production and adhere to international environmental accords. The ambiguous evidence for the Environmental Kuznets Curve underscores the need for more advanced models that account for structural differences among economies, including institutional quality, technological progress, and sectoral variations in emissions.

For economies that rely on natural resources, like Brunei and Indonesia, the main focus of policy should be on investing in renewable energy and diversifying the economy. These countries should promote clean energy projects and start new businesses that don't use fossil fuels to reduce their reliance on them. Encouraging oil-rich countries to use more renewable energy can help keep growth stable while lowering emissions intensity. Vietnam, Malaysia, and Thailand are examples of economies that rely on manufacturing. These countries should focus on using less energy, charging more for carbon, and using cleaner industrial technologies. Policies should help modernize production systems, encourage the use of low-carbon technologies, and give businesses that export eco-friendly goods tax breaks. This will help these countries stay competitive while also making sure that industrial growth is in line with environmental goals. Singapore and the Philippines, which have economies based on services, should put green finance and innovation ecosystems at the top of their lists. Strengthening financial tools for long-term investments, such as creating regional standards for green bonds, can encourage new ideas and speed up the shift to a low-carbon and knowledge-based economy across ASEAN. ASEAN's regional cooperation could make it easier to create a joint carbon credit market and integrate renewable energy across borders, which would help all of us reach our net-zero goals faster.

5.2 Limitations

This analysis offers substantial insights into the interplay between economic growth, CO_2 emissions, and trade openness in Southeast Asia; yet, it is constrained by certain constraints. The dataset, spanning from 1990 to 2022, may not fully capture the long-term effects of recently implemented environmental legislation or worldwide disruptions such as the COVID-19 pandemic; a more extensive dataset might improve the analysis. The modeling strategy, predominantly employing quadratic and cubic parameters, produces valuable but inconclusive results, as the relationship between GDP

and emissions is highly complex and may require more advanced econometric methods. The heterogeneity of Southeast Asian economies, marked by differences in industrial compositions, energy sources, and regulatory systems, suggests that trade liberalization affects emissions variably across each case. Thus, more thorough country-specific analysis would provide a clearer comprehension. Ultimately, the findings may lack applicability to other regions with distinct economic and environmental contexts, as the study focused exclusively on Southeast Asia.

This study utilizes OLS estimation primarily as a preliminary empirical investigation, owing to data constraints and inconsistent temporal coverage among countries. Future research will utilize sophisticated panel data techniques, including fixed or random effects, FMOLS, and DOLS estimators, to improve robustness and account for cross-sectional dependence

5.2 Future Research Directions

This study provides significant insights into the relationship among economic growth, CO_2 emissions, and trade openness in Southeast Asia; however, it is limited by several constraints. The dataset, covering the period from 1990 to 2022, may inadequately reflect the long-term impacts of newly enacted environmental policies or worldwide disturbances like the COVID-19 pandemic; a more comprehensive dataset would enhance the analysis. The modeling strategy, primarily utilizing quadratic and cubic parameters, yields valuable although ambiguous results, as the relationship between GDP and emissions is intricate and may necessitate more sophisticated econometric techniques. The diversity of Southeast Asian economies, characterized by variations in industrial structures, energy sources, and regulatory frameworks, indicates that trade liberalization influences emissions differently across contexts. Consequently, more comprehensive country-specific analysis would yield enhanced understanding. The findings may ultimately lack relevance to other regions with different economic and environmental situations, given the study concentrated exclusively on Southeast Asia.

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