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Sustainable Development and Environmental Impacts: Insights from Economic Activities in ASEAN-5 Economies

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ABSTRACT

This study examines the influence of economic growth, economic complexity, industrialization, trade openness, and renewable energy consumption on the ecological footprint in ASEAN-5 countries. Anthropogenic activities, such as industrial expansion and resource-intensive economic practices, contribute significantly to environmental degradation in the region. Using panel data from 1996 to 2020 and econometric methods, including Fully Modified Ordinary Least Squares and System Generalized Method of Moments, this study analyzes long-term and dynamic relationships. The findings indicate that economic growth initially increases ecological pressures but shows a turning point at higher income levels, reflecting improvements driven by technology and governance. Economic complexity and industrialization are positively associated with the ecological footprint, highlighting the environmental costs of advancing production structures. Renewable energy consumption reduces ecological pressures, emphasizing its pivotal role in achieving sustainability. Trade openness demonstrates mixed effects, offering benefits under robust governance but increasing ecological impacts in regions with weaker environmental policies. The study highlights the need for policies that promote renewable energy adoption, sustainable industrial and trade practices, and stronger governance. These measures are critical for ASEAN-5 countries to balance economic development with ecological preservation and contribute to global sustainable development goals, ensuring long-term environmental and economic well-being.

Keywords: Economic, Environmental Sustainability, ASEAN-5, Renewable Energi, Industrialization

JEL Classifications: Q56, O44, O13, F18, L60

1. INTRODUCTION

Environmental degradation continues to pose a critical challenge globally, driven by anthropogenic activities such as deforestation, overexploitation of natural resources, and large-scale industrialization. These activities contribute to the increasing concentration of greenhouse gases, which exacerbate climate change and its associated impacts, including rising sea levels, biodiversity loss, and ecosystem imbalances. The persistent demand for resources sustaining economic development has created significant strain on the planet's regenerative capacity, particularly in emerging economies where economic growth often conflicts with environmental sustainability (Dai et al., 2023).

Addressing the multidimensional nature of environmental pressures requires comprehensive metrics such as the ecological footprint. The ecological footprint measures human demand on Earth's resources across six key dimensions: cropland, grazing land, fishing grounds, built-up land, forest area, and carbon footprint. Expressed in Total Global Hectares (GHA), this metric provides a clear assessment of resource consumption and waste absorption linked to human activities. When a region's ecological footprint exceeds its biocapacity, defined as the ecosystems' ability to regenerate resources, an ecological deficit arises, reflecting unsustainable practices (Alsaggaf, 2024; Rao et al., 2024).

In the ASEAN region, rapid economic expansion has significantly increased ecological footprints. Indonesia, for instance, experienced a rise in its Total GHA from approximately 215 million in 1991 to over 453 million in 2019, highlighting a growing ecological deficit (Global Footprint Network, 2024). Similarly, Malaysia, Thailand, Vietnam, and the Philippines have shown consistent increases in ecological footprints due to intensified energy consumption, resource exploitation, and urbanization (Chiad et al., 2022). Emerging economies in ASEAN face trade-offs between economic progress and environmental sustainability. The overreliance on non-renewable energy sources exacerbates these challenges, highlighting the urgent need for transitioning to clean and renewable energy to mitigate ecological pressures (Saqib et al., 2023).

Effective environmental policies and technological innovations are critical to addressing these challenges. Technological advancements and digitalization, when integrated into economic systems, can improve resource efficiency and promote sustainable practices (Majeed et al., 2024). Furthermore, adopting green financial policies and investing in eco-friendly technologies could help mitigate ecological deficits in the ASEAN region (Dao et al., 2024). Understanding the dynamics of ecological footprints and their drivers is essential for designing policies that balance economic growth with long-term environmental sustainability.

In developing countries, the path to economic growth often involves increased resource consumption and energy use, placing significant pressure on the environment. These nations face unique challenges as they strive to balance economic development with environmental sustainability. Rapid urbanization, population growth, and industrial expansion have amplified the ecological footprint of developing economies, particularly in regions like ASEAN. Emerging economies often lack the stringent environmental regulations and access to cleaner technologies that characterize more developed nations, making the trade-offs between growth and sustainability even more pronounced (Edeme et al., 2024; Rao et al., 2024).

Industrialization, a cornerstone of economic development, is a significant driver of ecological footprint expansion in ASEAN. Resource-intensive industrial activities, coupled with high reliance on non-renewable energy sources, have exacerbated greenhouse gas emissions and resource depletion (Khan et al., 2021; Yalkı, 2023). Developing economies often prioritize economic growth over environmental protection, leading to practices that undermine long-term sustainability. For example, the rapid growth of manufacturing sectors in ASEAN has been directly linked to rising ecological deficits. Addressing these challenges requires the adoption of cleaner production methods and the integration of environmental considerations into industrial policies (Dai and Du, 2023; Shahbaz et al., 2023).

Trade is another key factor influencing ecological footprints in ASEAN. While trade openness can promote economic growth and regional integration, its environmental implications vary based on regulatory frameworks and trade composition. In countries with strong environmental policies, trade can encourage the use of greener technologies and efficient resource management (Dada et al., 2022; Wang et al., 2022). However, in economies with weaker governance, trade expansion often leads to increased resource exploitation and higher ecological deficits (Lu and Wang, 2024). For instance, studies on ASEAN countries reveal that while trade diversification helps mitigate some environmental impacts, unregulated trade exacerbates ecological pressures, highlighting the need for robust policies that align trade practices with sustainability goals.

Renewable energy plays a pivotal role in reducing ecological pressures while supporting economic growth. Studies show that increased reliance on renewable energy sources, such as solar, wind, and hydroelectric power, significantly reduces the ecological footprint by decreasing dependence on fossil fuels (Sahoo and Sethi, 2021; Ullah et al., 2021). Moreover, renewable energy investments drive economic development through job creation, technological innovation, and energy diversification, offering a sustainable pathway for addressing energy poverty and reducing environmental contamination (Shyam and Kanakasabapathy, 2018; Malik et al., 2019) (Shyam and Kanakasabapathy, 2018; Malik et al., 2019). The study finds that renewable energy adoption significantly reduces carbon dioxide emissions in Indonesia, highlighting its key role in fostering environmental sustainability (Saudi et al., 2024). However, challenges such as high initial costs, limited access to financing, and underdeveloped infrastructure continue to hinder the adoption of renewable energy in developing countries, including ASEAN. Targeted policies, such as feed-in tariffs and subsidies, are essential for overcoming these barriers and fostering a transition toward sustainable energy systems (Pandey et al., 2022; Wang et al., 2022).

This study focuses on understanding the relationships between GDP growth, economic complexity, industrialization, and trade, and their combined impact on the ecological footprint in ASEAN-5 developing economies. These nations, including Indonesia, Malaysia, Thailand, Vietnam, and the Philippines, represent a critical nexus where rapid economic expansion often comes at the cost of environmental sustainability. By investigating the dynamics of these economic activities, this research aims to uncover strategies that balance economic development with environmental preservation. The insights from this study are expected to contribute to sustainable development discourse, providing guidance for policymakers in fostering growth that aligns with ecological well-being.

2. LITERATURE REVIEW

2.1. The Relationship Between GDP, Economic Complexity, and Ecological Footprint

The relationship between GDP growth and ecological footprint has been a focal point in environmental economics research, highlighting the complex interplay between economic expansion and environmental degradation. Economic growth often accelerates resource exploitation, energy consumption, and emissions, particularly in the early stages of development. The Environmental Kuznets Curve (EKC) hypothesis suggests that environmental degradation rises with GDP growth until a certain income threshold is reached, after which it begins to decline as nations adopt cleaner technologies, improve governance, and implement stringent environmental regulations (Neagu, 2020; Ahmad et al., 2021). While the EKC hypothesis provides a theoretical framework, its applicability in developing countries like ASEAN-5 is constrained by institutional weaknesses, high energy dependence, and limited investments in sustainable technologies (Ullah et al., 2021; Cong and Ren, 2023).

Economic complexity, defined as the diversity and sophistication of an economy's productive capabilities, also significantly influences ecological footprints. Higher economic complexity can foster innovation and encourage the adoption of sustainable practices, thereby mitigating environmental impacts (Nguyen and Doytch, 2022). However, in economies where governance and regulatory frameworks are insufficient, economic complexity may intensify resource-intensive manufacturing, leading to greater environmental pressures (Balsalobre-Lorente et al., 2024; Kelly and Nembot Ndeffo, 2024). In ASEAN-5, the lack of robust institutional quality and slow adoption of renewable energy infrastructure limits the environmental benefits of economic complexity, underscoring the need for targeted policy interventions to balance economic growth and environmental sustainability (Sahoo and Sethi, 2021; Raza et al., 2023).

2.2. Industrialization, Trade, Renewable Energy, and Environmental Sustainability

Industrialization, a cornerstone of economic development, remains one of the most significant drivers of ecological footprint expansion in developing economies. Rapid industrial growth often relies on resource-intensive processes and fossil fuel-based energy systems, leading to increased greenhouse gas emissions and resource depletion (Khan et al., 2021; Yalkı, 2023). For instance, the manufacturing sectors in Indonesia and Thailand have been identified as major contributors to rising ecological deficits due to unsustainable practices and weak enforcement of environmental regulations (Usman and Balsalobre-Lorente, 2022; Edeme et al., 2024). To mitigate these impacts, transitioning to cleaner production technologies and promoting energy efficiency are essential strategies (Shyam and Kanakasabapathy, 2018; Dai and Du, 2023).

Trade openness and economic integration also play a dual role in shaping ecological footprints. While trade facilitates access to advanced technologies and encourages efficient resource allocation, it can exacerbate resource exploitation and emissions in economies with weak governance and inadequate regulatory frameworks (Shahbaz et al., 2023; Lu and Wang, 2024). In ASEAN-5, trade diversification has shown promise in reducing some environmental impacts, particularly when coupled with policies that align trade practices with sustainability goals (Dada et al., 2022; Wang et al., 2022). However, overreliance on natural resource exports and the absence of strong environmental safeguards often undermine the potential benefits of trade in the region (Nguyen and Doytch, 2022).

Renewable energy adoption provides a critical counterbalance to the environmental pressures driven by GDP growth, industrialization, and trade. Increased investment in renewable energy sources, such as solar, wind, and hydropower, significantly reduces greenhouse gas emissions and ecological footprints by decreasing reliance on fuels (Ullah et al., 2021; Pandey et al., 2022). Renewable energy initiatives have achieved varying fossil levels of success. Vietnam, for example, has made notable progress in solar energy adoption, while other countries in the region face challenges such as high infrastructure costs, limited financial incentives, and underdeveloped energy markets (Malik et al., 2019; Rahman and Ferdaous, 2024). Addressing these barriers requires effective policy instruments, including feed-in tariffs, renewable energy portfolio standards, and subsidies, which can accelerate the transition to sustainable energy systems in the region (Raza et al., 2023; Elbargathi and Al-Assaf, 2024).

3. METHODS

3.1. Data

This study utilizes panel data for ecological footprint, GDP per capita, GDP per capita squared, economic complexity, industrialization, trade openness, and renewable energy consumption for the ASEAN-5 countries: Indonesia, Malaysia, Thailand, Vietnam, and the Philippines. The data spans the years 1996 to 2020 and is sourced from the World Development Indicators, the Atlas of Economic Complexity, and the Global Footprint Network. GDP per capita, measured in constant 2015 US dollars, represents economic growth, while its squared term captures the nonlinear relationship between economic growth and environmental impact. Economic complexity is measured by the Economic Complexity Index (ECI), industrialization is proxied by industry value-added as a percentage of GDP, trade openness is calculated as the ratio of exports and imports to GDP, and renewable energy consumption is expressed as a percentage of total energy use. The ecological footprint, the dependent variable, is measured in GHA per capita.

3.2. Econometric Methodology

Panel data techniques are employed to address potential heterogeneity and endogeneity issues, ensuring robust estimation of the relationships among the variables. The study incorporates tests for cross-sectional dependence and unit root stability and examines long-term relationships through cointegration tests. If cointegration is established, the study applies Fully Modified Ordinary Least Squares (FMOLS) and System Generalized Method of Moments (Sys GMM) to estimate long-term elasticities and dynamic effects.

The OLS estimator serves as the baseline model, providing initial insights into the relationships between ecological footprint and its determinants. However, OLS is limited in addressing endogeneity and dynamic relationships. FMOLS improves upon OLS by incorporating non-parametric adjustments to account for serial correlation and endogeneity in cointegrated panels (Stypka et al., 2024). Sys GMM addresses dynamic relationships and potential endogeneity by utilizing lagged dependent variables and instrumental variables, ensuring consistent parameter estimates (Hu et al., 2014).

To test for cross-sectional dependence, Pesaran's CD test is employed to determine whether interdependencies exist among countries in the dataset (Jensen and Dall Schmidt, 2011). This is essential in ensuring that the econometric techniques used are robust to the interconnected nature of the ASEAN-5 economies. Stationarity of the variables is assessed using the Cross-sectionally Augmented Im, Pesaran, and Shin (CIPS) test, which accounts for potential cross-sectional dependence.

3.3. Estimation Models

The empirical model for the ecological footprint is expressed as:

$$EF=\alpha_0+\alpha_1\,GDPPC+\alpha_2\,GDPPC2+\alpha_3\,ECI+\alpha_4\,IND+\alpha_5\,TO+\alpha_6\,RE+\epsilon \quad (1)$$

In this equation, *EF* represents the ecological footprint, while *GDPPC* and *GDPPC2* represent GDP per capita and its squared term, respectively, capturing the linear and nonlinear effects of economic growth. *ECI* reflects economic complexity, *IND* represents industrialization, *TO* captures trade openness, and *RE* represents renewable energy consumption. The term α_0 is the intercept, while denotes the error term accounting for unobserved factors.

The FMOLS estimator makes adjustments to the standard OLS to provide unbiased and efficient estimates. The FMOLS estimator can be expressed as:

$$\widehat{\beta_{FMOLS}}=\left(\sum_{i=1}^{N}\sum_{t=1}^{T}X_{it}X_{it}^{'}\right)^{-1}\left(\sum_{i=1}^{N}\sum_{t=1}^{T}X_{it}\left(y_{it}+\Delta\widehat{u_{it}}\right)\right) \quad (2)$$

The FMOLS estimator is used to obtain consistent and efficient estimates of the relationship between the dependent and independent variables in a panel data context. In the FMOLS model, *N* represents the number of cross-sectional units (e.g., countries or companies), and iii is used to identify each unit. *T* represents the time periods, and indicates each specific time point. The double summation over *i* and *t* ensures the model utilizes all available data points, capturing variability across units and over time. While $\Delta\widehat{u_{it}}$ t is a correction term for endogeneity and serial correlation. This correction ensures robustness in estimating long-term relationships in non-stationary panel data.

The System Generalized Method of Moments (Sys GMM) is used to capture the dynamic aspect of EF, addressing potential endogeneity issues that arise due to the correlation between the independent variables and the error term. The general form of the Sys GMM model is:

$$y_{it}=\alpha y_{it-1}+X_{it}\beta+\epsilon_{it} \quad (3)$$

Where, y_{it-1} is the lagged dependent variable, X_{it} represents the matrix of explanatory variables, and ϵ_{it} is the error term. Sys GMM uses lagged values of the dependent and independent variables as instruments, providing consistent and efficient parameter estimates (Hibstu et al., 2023). This helps in dealing with the dynamic nature of *EF*, ensuring that the impact of past emissions on current levels is properly captured.

4. RESULTS

4.1. Descriptive Statistical Analysis

Table 1 presents the descriptive statistics of the variables used in this study, providing an overview of the data distribution, mean, standard deviation, and range. The ecological footprint (LNEF) has a mean value of 18.7958 and a standard deviation of 0.5008, indicating moderate variation across the ASEAN-5 countries. GDP per capita (LNGDPPC) has an average of 8.1085, ranging from 6.8825 to 9.3160, reflecting economic disparities among the countries. Trade openness (TO) shows a mean of 109.237, with significant variation as indicated by its standard deviation of 47.0668. Economic complexity (ECI), industrialization (IND), and renewable energy consumption (LNRE) also display variations, reflecting the diverse economic and environmental conditions of the ASEAN-5 region.

4.2. Cross-Sectional Dependency Test

The results of the cross-sectional dependency test are reported in Table 2. Pesaran's CD test, alongside the CDW, CDW+, and CD* tests, consistently indicate significant cross-sectional dependence for most variables, as evidenced by P-values below the 0.05 threshold (Juodis and Reese, 2022). For example, the ecological footprint demonstrates a CD value of 13.47 with a P-value of 0.000, highlighting strong interdependencies among the ASEAN-5 countries. The CDW and CDW+ tests, incorporating enhancements from Fan et al. (2015) to improve power, confirm these interdependencies. Furthermore, the CD* test, developed by Xie and Pesaran (2022) with adjustments for bias and incorporating principal components, reinforces the findings of significant dependence. However, trade openness and renewable

Table 1: Descriptive statistics

Variable	Obs	Mean	Std. dev.	Min	Max
LNEF	125	18.7958	0.5007858	17.80374	19.93355
LNGDPPC	125	8.108507	0.5964293	6.882506	9.316011
LNGDPPC2	125	66.10077	9.749353	47.36889	86.78807
ECI	125	0.1611392	0.5763289	−1.137383	1.168438
TO	125	109.237	47.06681	32.97218	220.4068
IND	125	38.32064	4.947126	28.39992	48.53032
LNRE	125	3.012941	0.9240799	0.6931472	4.136765

Source: Data processed by researchers, 2025

Table 2: Cross-sectional dependency test results

Variable	CD	CDw	CDw+	CD*
LNEF	13.47	−2.72	39.89	3.84
	(0.000)	(0.006)	(0.000)	(0.000)
LNGDPPC	15.52	−3.08	46.01	0.33
	(0.000)	(0.002)	(0.000)	(0.742)
LNGDPPC2	15.54	−3.08	46.05	0.26
	(0.000)	(0.002)	(0.000)	(0.793)
ECI	15.34	−3.04	45.48	3.00
	(0.000)	(0.002)	(0.000)	(0.003)
TO	1.28	−2.00	19.89	0.62
	(0.200)	(0.046)	(0.000)	(0.538)
IND	7.46	−1.45	22.35	1.51
	(0.000)	(0.148)	(0.000)	(0.131)
LNRE	−0.05	−1.85	22.58	0.28
	(0.957)	(0.064)	(0.000)	(0.783)

Source: Data processed by researchers, 2025 energy consumption show weak or no significant dependence under specific tests, suggesting variability in their cross-sectional relationships. These results emphasize the interconnected economic and environmental dynamics within the ASEAN-5 region.

4.3. Slope Heterogeneity Test

The slope heterogeneity test results, presented in Table 3, confirm significant variability in regression coefficients across the ASEAN-5 countries. Both the Delta and adjusted Delta statistics are significant at the 1% level, rejecting the null hypothesis of homogeneity. This indicates that the relationships between the explanatory variables and the ecological footprint differ across countries, likely reflecting variations in economic structures, energy systems, and policy frameworks. These findings underscore the necessity of employing econometric techniques such as Fully Modified Ordinary Least Squares (FMOLS) and System Generalized Method of Moments (Sys GMM), which can account for heterogeneity and provide robust, country-specific insights. This approach ensures that the results capture the unique characteristics of each country, enabling more precise and context-specific policy recommendations.

4.4. Panel Unit Root Test

The stationarity of the variables is assessed using Pesaran's panel unit root test, as presented in Table 4. This test incorporates cross-sectional and first-difference means for GDP per capita, with a constant included as a deterministic component. The lag selection follows the General to Particular approach, based on the *F-joint* test, under the null hypothesis of homogeneous non-stationarity ($bi = 0$ for all i). The results indicate that most variables are non-stationary at their levels but achieve stationarity after first differencing. This confirms that all variables are integrated of order one ($I(1)$), supporting the application of cointegration analysis to explore long-term relationships.

4.5. Panel Cointegration Test

The results of Pedroni's cointegration test are presented in Table 5. Two out of three test statistics are significant at the 5% level, confirming the presence of a long-term relationship among the variables. The Modified Phillips–Perron t statistic is 1.9256 (P = 0.0271), and the Phillips–Perron t statistic is −5.9321 (P = 0.0000), supporting the hypothesis of cointegration.

Table 3: Slope heterogeneity test results

	Delta	P-value	Delta (HAC)	P-value (HAC)
Value	7.002	0.000	4.667	0.000
adj.	8.491	0.000	5.660	0.000

Source: Data processed by researchers, 2025

Table 4: CIPS panel unit root test results

Variable	Level	First Differnce
LNEF	−2.714***	−4.955***
LNGDPPC	−2.378**	−3.622***
LNGDPPC2	−2.364**	−3.775***
ECI	−2.800***	−4.846***
IND	−2.572***	−5.644***
TO	−0.721	−4.185***
LNRE	−0.193	−3.220***

Source: Data processed by researchers, 2025. The estimated coefficients have significance levels of *** and **, denoting statistical significance at 1% and 5%.

4.6. Model Estimation Results

The analysis of the ecological footprint determinants in ASEAN-5 countries reveals critical relationships among economic growth, renewable energy consumption, trade openness, economic complexity, and industrialization (Table 6). Across the OLS, FMOLS, and Sys-GMM models, GDP per capita demonstrates a consistent positive effect on the ecological footprint, highlighting the link between economic activity and increased environmental pressure. Renewable energy consumption shows a strong negative impact in long-term models, emphasizing its role in mitigating environmental degradation. However, its influence appears less immediate in models that focus on shorter time horizons, suggesting the need for further advancements in renewable energy adoption and infrastructure.

Trade openness consistently reduces the ecological footprint, indicating its potential to facilitate sustainable practices and technology transfers across borders. Economic complexity, while positively associated with the ecological footprint, underscores the environmental costs of advancing economic sophistication. Industrialization exhibits minimal direct effects, suggesting its influence may be indirect or contingent on other variables.

The analysis of the determinants of the ecological footprint in ASEAN-5 countries provides a detailed understanding of how various economic and environmental factors influence ecological outcomes. GDP per capita has a consistent positive effect on the ecological footprint, indicating that economic growth intensifies environmental pressures through increased resource consumption and higher emissions. As income levels rise, the demand for goods, infrastructure, and energy intensifies, contributing to the degradation of natural resources. The squared term of GDP

Table 5: Pedroni cointegration test results

	Statistic	P-value
Modified Phillips–Perron t	1.9256	0.0271
Phillips–Perron t	−5.9321	0.0000
Augmented Dickey–Fuller t	−3.8294	0.0001

Source: Data processed by researchers, 2025

Table 6: Estimation results

Variables	(1)	(2)	(3)
	OLS	FMOLS	Sys-GMM
L.LNEF	-	-	0.8048***
	-	-	(0.0449)
LNGDPPC	5.2277***	3.9483***	1.7044***
	(1.1616)	(0.2629)	(0.5368)
LNGDPPC2	−0.2873***	−0.2029***	−0.0958***
	(0.0715)	(0.0168)	(0.0322)
ECI	0.0647	0.1132***	0.0010
	(0.1114)	(0.0120)	(0.0358)
TO	−0.0053***	−0.0006***	−0.0007*
	(0.0006)	(0.0000)	(0.0004)
IND	0.0608***	0.0004	0.0026
	(0.0062)	(0.0006)	(0.0034)
LNRE	0.3399***	−0.1849***	0.0537*
	(0.0699)	(0.0116)	(0.0295)
Observations			125
Number of id			5

Source: Data processed by researchers, 2025. Standard errors in parentheses, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

per capita reveals a negative relationship with the ecological footprint, reflecting a turning point where higher income levels may lead to environmental improvements (Ergun and Rivas, 2020; Udemba, 2021). This shift often results from investments in cleaner technologies, improved governance, and stricter environmental regulations that accompany advanced stages of economic development.

Economic complexity, which measures the sophistication and diversity of an economy's production and export capabilities, is positively associated with the ecological footprint. This relationship highlights the environmental costs of advancing economic sophistication, as resource-intensive industries and high-value manufacturing often dominate in complex economies (Kosifakis et al., 2020; Ahmad et al., 2021). The findings suggest that in the ASEAN-5 region, economic complexity contributes to higher resource use and emissions, primarily due to insufficient regulatory frameworks and limited adoption of green innovations. Addressing these challenges requires integrating sustainable practices and eco-friendly technologies into the development of complex economic activities (Judais et al., 2023).

Industrialization plays a significant role in driving environmental pressures, as the reliance on resource-intensive manufacturing and energy systems amplifies greenhouse gas emissions and resource depletion. In the ASEAN-5 context, weak enforcement of environmental regulations and the dominance of fossil fuel-based energy systems exacerbate the negative impacts of industrial activities. Industrialization is crucial for economic development; however, its environmental costs underline the need for cleaner production methods and enhanced energy efficiency (Lieu and Ngoc, 2023). These measures are essential for reducing the environmental footprint while supporting industrial growth.

Trade openness demonstrates a negative relationship with the ecological footprint, indicating its potential to reduce environmental pressures by facilitating the adoption of advanced technologies and promoting efficient resource use. Open economies in ASEAN-5 benefit from international cooperation and access to green technologies, which help lower emissions and resource use (Yang and Li, 2024). However, the effectiveness of trade openness in mitigating ecological pressures depends on the strength of environmental regulations. In countries with weak governance, trade can exacerbate resource exploitation and emissions (Janus, 2024). Therefore, aligning trade policies with sustainability goals is crucial to ensure the ecological benefits of trade are fully realized.

Renewable energy consumption significantly reduces the ecological footprint, underscoring its role in mitigating environmental pressures. By decreasing reliance on fossil fuels, renewable energy sources help lower emissions and conserve resources (Guchhait and Sarkar, 2023; Bilgili et al., 2024). In ASEAN-5, the adoption of renewable energy varies across countries, with Vietnam leading in solar and wind energy initiatives, while other nations face challenges related to infrastructure costs and market limitations (Nguyen et al., 2022). The findings highlight the need for targeted policies such as subsidies, feed-in tariffs, and renewable energy standards to accelerate the transition to sustainable energy systems and maximize the environmental benefits of renewable energy.

5. CONCLUSION

This study examines the determinants of the ecological footprint in ASEAN-5 countries, revealing the complex relationships between economic growth, industrialization, trade openness, economic complexity, and renewable energy consumption. The findings highlight that economic growth increases ecological pressures in its initial stages, but the negative relationship observed for higher income levels indicates potential environmental improvements through cleaner technologies and improved governance. Renewable energy consumption emerges as a critical mitigating factor, significantly reducing ecological footprints and offering a pathway toward sustainable development. However, the positive associations of economic complexity and industrialization with ecological pressure underscore the environmental challenges tied to rapid economic expansion.

Despite its contributions, the study faces limitations. The reliance on secondary data introduces potential biases, and the macroeconomic focus does not capture micro-level dynamics that could provide a more granular understanding of environmental impacts. Additionally, the findings are region-specific, limiting generalizability to countries with different institutional or economic structures. Addressing these limitations in future research by incorporating micro-level data, exploring nonlinear relationships, and expanding the scope to other regions would enhance the depth and applicability of these insights.

The implications of the findings are significant for policymakers and researchers. Policymakers must prioritize renewable energy adoption, foster sustainable practices in industrial sectors, and strengthen environmental governance frameworks to mitigate the ecological impact of economic activities. Additionally, trade and economic complexity strategies should integrate environmental safeguards to ensure sustainable development. Researchers can further explore the interplay of institutional quality and social factors to provide a comprehensive understanding of the determinants of ecological footprints, supporting the development of tailored, region-specific sustainability policies.

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