“Foreign direct investment and manufacturing CO_2 emissions in ASEAN”

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FOREIGN DIRECT INVESTMENT AND MANUFACTURING CO_2 EMISSIONS IN ASEAN

Abstract

This study examines how foreign direct investment (FDI) has affected manufacturing carbon emissions in eight ASEAN economies from 2005 to 2022 using panel data from the World Bank and UNCTAD and employing random effects and feasible generalized least squares estimators. The preferred specification indicates that a 1 percentage point increase in manufacturing-adjusted FDI inflows (as a share of GDP) is associated with a 0.018-unit rise in log manufacturing CO_2 emissions (approximately 1.8%). Simultaneously, population size (coefficient ≈ 0.94) and fossil fuel energy consumption (coefficient ≈ 0.053) exert strong positive and statistically significant effects. By contrast, per capita income and its squared term are not significant, providing no support for a Kuznets type nonlinear income-emissions relationship, and lagged emissions add little once contemporaneous drivers and error structures are controlled for. The results suggest that FDI has primarily flowed into emissions-intensive manufacturing activities, with limited evidence of broad-based clean technology transfer, thereby risking a lock-in of carbon-intensive development that undermines ASEAN's Net Zero ambitions and intergenerational equity. The paper argues that tighter environmental standards for FDI, an accelerated energy transition away from fossil fuels, and integrated population planning is needed to reconcile manufacturing-led industrial expansion with sustainability goals in ASEAN. It also offers sector specific evidence to guide FDI governance and energy policy in middle-income countries.

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INTRODUCTION

The Association of Southeast Asian Nations (ASEAN) has emerged as a major hub for foreign direct investment (FDI), attracting approximately US$230 billion in inflows in 2023, or roughly 17% of the global total (ASEAN, 2024), with manufacturing absorbing a substantial share of this capital. Simultaneously, the expansion of energyintensive manufacturing has contributed to rising greenhouse gas emissions. Regional CO_2 emissions exceeded 4,000 Mt in 2021 and are projected to continue increasing, which challenges ASEAN's NetZero and broader sustainable development commitments (Energy Asia, 2025). These developments raise a central question: Does FDI primarily intensify carbon pressures in host economies, or can it support greener growth through cleaner technologies and more efficient production processes?

Empirical evidence on the FDI–emissions nexus is mixed, reflecting differences in institutional quality, regulatory frameworks, and income levels, and much of the existing research either aggregates the economy or examines singlecountry cases in Asia. Consequently, sectorspecific evidence on manufacturingoriented FDI remains limited in the ASEAN context. In particular, little is known about how FDI in manufacturing, as both a key driver of industrialization and a ma-

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jor source of CO_2, shapes the environmental trajectory of middleincome economies in the region. This study examines the impact of FDI on manufacturing CO_2 emissions in Brunei, Cambodia, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam over 2005–2022. It uses a balanced panel to capture how FDI, population dynamics, and fossil fuel dependence jointly drive sectoral emissions. This study provides new sector-specific evidence and highlights the implications for FDI governance and energy policies. It is intended to support ASEAN governments in shifting foreign investment away from carbonintensive activities and toward greener, more inclusive industrial growth.

1. LITERATURE REVIEW

Foreign direct investment (FDI) is generally understood as crossborder investment that combines capital transfer with lasting managerial control in the host economy (OECD, 2025), and CO_2 emissions are widely used as a proxy for environmental degradation in empirical research. The academic discourse on the environmental impact of foreign direct investment (FDI) is primarily grounded in three key theoretical frameworks: the pollution haven hypothesis (PHH), pollution halo hypothesis, and Environmental Kuznets Curve (EKC). The PHH posits that FDI inflows can exacerbate carbon emissions in developing economies, typically characterized by less stringent environmental regulations. Foundational studies, including Copeland and Taylor (2004), argue that multinational corporations often relocate pollution-intensive operations to jurisdictions with more relaxed standards, thereby minimizing regulatory compliance costs. Eskeland and Harrison (2003) support this notion, emphasizing comparative advantage of pollution control across countries. Likewise, Grimes and Kentor (2003) documented a concentration of FDI in energy-intensive sectors that further amplifies carbon emissions in host nations. Recent studies have further confirmed that FDI inflows can induce the relocation of polluting industries to developing economies with laxer environmental regulations, thereby increasing local emissions (Boateng et al., 2024; Nguyen & Ho, 2021). This body of evidence from ASEAN and beyond supports the PHH, showing that competitive FDI attraction can shift 'dirty' industries and outdated manufacturing practices to developing countries, thereby raising CO_2 emissions and worsening environmental degradation.

Conversely, the pollution halo hypothesis presents an optimistic alternative, suggesting that FDI can facilitate environmental improvements by transferring advanced technologies and management practices. Melane-Lavado et al. (2018) argue that FDI from developed countries often introduces cleaner production technologies, elevates labor productivity, and lowers emissions per unit output. Gunarto (2020) shows that FDI serves as a conduit for skill enhancement and the adoption of international environmental standards, enabling local firms to comply more effectively and reduce overall emissions. Empirical studies have noted that institutional quality often mediates these effects, with stronger governance increasing the likelihood that FDI leads to positive environmental externalities rather than degradation.

The EKC provides a nuanced perspective on the dynamic between economic growth and environmental quality. It postulates a nonlinear, inverted U-shaped relationship: in early stages of economic expansion, industrialization, and resource exploitation drive up emissions and environmental degradation. Once a critical threshold of per capita income is surpassed, economic structures typically shift toward services and high-tech sectors, and societal demand for environmental stewardship intensifies. Together, these changes lead to a gradual reduction in carbon emissions.

Grossman and Krueger (1995) first formalized this concept, and subsequent reviews have emphasized that progressive environmental awareness and robust policy interventions are often necessary to realize the downward segment of the EKC (Yandle et al., 2004; Stern, 2004). Recent sector-specific studies from Southeast Asia further support these insights, highlighting the importance of policy measures and public awareness in achieving sustainable development (Kirikkaleli et al., 2023).

Overall, these theoretical perspectives have important implications for the development trajectories of FDI-dependent emerging economies such

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as those in ASEAN. When pollution-intensive FDI coincides with weak institutions, lax environmental regulations, and limited enforcement capacity, host countries risk being locked into carbon-intensive development paths. These paths are costly to reverse and undermine long-term progress toward sustainable and inclusive growth. In such settings, FDI can entrench obsolete technologies, deepen structural dependence on fossil fuels, and shift environmental and social burdens onto vulnerable communities.

In contrast, where host governments design and implement robust regulatory frameworks, credible environmental standards, and targeted industrial policies, FDI can serve as a conduit for leapfrogging to cleaner technologies and higher value-added activities. Under strong governance and effective policy coordination, foreign investors may be induced to adopt international best practices, transfer advanced low-carbon technologies, and support the creation of greener production networks. This dual potential of FDI underlines the central role of institutions and policy design in shaping development outcomes, as FDI can either reinforce a carbon-intensive development trap or enable a transition toward low-carbon industrialization.

The empirical literature investigating the link between foreign direct investment (FDI) and carbon emissions in international and regional contexts reveals substantial heterogeneity in findings. Broadly, existing studies can be grouped into three strands: evidence consistent with the pollution haven effect, evidence supporting a pollution halo effect under stronger institutional conditions, and mixed or context-dependent findings. For instance, Febriyanto et al. (2024) applied the ARDL model and found that FDI increased CO_2 emissions in Singapore and Vietnam, but did not exert a statistically significant influence in Indonesia and Malaysia. Wang et al. (2023) observed a nonlinear relationship, demonstrating that FDI tends to increase emissions in lower-income countries while potentially reducing them in high-income settings, suggesting the pivotal role of developmental stages and policy environments. Cole et al. (2017), through a meta-analysis, emphasized the variable nature of FDI's impact on CO_2 emissions, with outcomes contingent upon the economic sector, host-country institutions, and the origin of foreign capital. In the context of Asia, Soukaina and Kammoun (2025) reported that while FDI raised emissions in China in the short and long run, the impact in India was largely transitory. Shaari et al. (2014) found no significant effect of FDI on CO_2 emissions across 15 Asian economies during their observation period. Conversely, Yu et al. (2024) demonstrated that FDI contributes to increased carbon emissions in developing countries, primarily because it is concentrated in manufacturing sector, whereas the effect is much weaker in developed nations (Soukaina & Kammoun, 2025; Nguyen et al., 2023; Febriyanto et al., 2023).

Studies on Vietnam have shown empirical ambiguity. For instance, Thu (2023) found technology transfer associated with FDI is effective in reducing emissions, whereas Nam et al. (2023) has concluded that FDI had opposing effects across time horizons, increasing emissions in the long term but facilitating reductions in the short run. Hưng (2024) and Huy (2024) documented significant, long-term, positive correlations between FDI and carbon emissions. In contrast, Phúc (2024) observed short-run emission reductions attributable to FDI. Studying ASEAN, Nguyen et al. (2023) reported a general tendency for FDI to be associated with emission increases but underscored the critical mitigating role of institutional quality in shaping these dynamics. Overall, this study provides considerable support for the pollution haven hypothesis in developing and emerging economies, including several ASEAN countries. In these settings, competitive pressures to attract foreign capital, combined with weaker environmental regulation and enforcement, appear to encourage the relocation of carbon-intensive production and reinforce fossil-fuel-based industrialization patterns.

A second strand of research highlights circumstances under which FDI is associated with improvements in environmental performance, often through technology transfer, management upgrades, and stricter compliance with international standards (Melane-Lavado et al., 2018; Gunarto, 2020). Studies focusing on economies with relatively stronger institutions and environmental governance document cases where foreign investors introduce cleaner production processes, raise energy efficiency, and reduce emission intensity, consistent with a pollution halo effect. In such contexts, FDI can complement domestic policy reforms by accelerating the diffusion of low-carbon technologies and reinforcing the credibility of regulatory framework.

A third group of studies reports mixed or nonlinear effects, indicating that the environmental impact of FDI is highly context-specific and may vary across time horizons, income levels, and sectors. Evidence from Vietnam, for example, shows that FDI can reduce emissions in the short run through technology transfer while contributing to higher emissions in the long run as manufacturing capacity expands. This pattern points to complex dynamic trade-offs. Similar patterns emerge in broader Asian samples, where institutional quality, energy structure, and development stage jointly determine whether FDI exacerbates or alleviates carbon pressures.

Despite this extensive literature, relatively few studies have explicitly focused on the manufacturing sector as a distinct locus of both development and environmental challenges, particularly within ASEAN. Existing research often aggregates across sectors or treats manufacturing only implicitly, limiting understanding of how FDI in this development engine interacts with country-specific institutional settings, energy systems, and industrial policies. This gap is especially important because manufacturing remains a key driver of structural transformation and export growth in ASEAN middle-income economies, while simultaneously constituting a major source of carbon emissions and lock-in risks.

Despite extensive investigation, consensus is lacking on the pathways through which FDI affects carbon emissions, owing to disparities in analytical frameworks, temporal and spatial coverage, and economic contexts. Most prior research has focused on single-country cases or broad regional analyses. As a result, it often overlooks the specific dynamics of the manufacturing sector, which is a principal source of emissions and a key target for FDI within ASEAN.

Addressing these limitations, the present study offers a focused examination of the impact of FDI on carbon emissions within the manufacturing sector of eight ASEAN nations, employing an updated panel dataset until 2022. This approach intends to provide a more accurate and contemporary assessment of the FDI-CO_2 linkage, accounting for the dual imperatives of advancing industrialization and fulfilling international climate commitments. By filling gaps in both topical coverage and temporal scope, this study aims to deliver new empirical evidence and practical policy recommendations to support the effective management of FDI and its environmental implications in ASEAN.

More specifically, this study advances the development literature in two main ways. First, it employs an updated panel dataset that extends until 2022. This coverage includes the post-Paris Agreement period in which ASEAN economies have increasingly articulated Net-Zero pledges and integrated climate considerations into their development strategies. This temporal coverage allows a more timely assessment of how FDI interacts with evolving sustainability commitments and policy frameworks in the region. Second, the analysis focuses explicitly on the manufacturing sector, which remains the core engine of industrialization and export-led growth in ASEAN middle-income economies but also represents one of their most significant carbon challenges. By concentrating on this sectoral nexus, this study provides granular evidence on how FDI-driven industrial development can both support and jeopardize the pursuit of low-carbon, inclusive development paths.

This study therefore pursues three specific aims. First, it estimates the direction and magnitude of the effect of manufacturing-oriented FDI inflows on sectoral CO_2 emissions across eight ASEAN economies over 2005 to 2022, employing panel estimators that correct for cross-sectional dependence, heteroscedasticity, and serial correlation. Second, the analysis examines whether co-determinants of manufacturing emissions, including per capita income and its squared term, population size, and fossil fuel energy consumption, exhibit patterns consistent with Environmental Kuznets Curve dynamics or pollution haven mechanisms in the ASEAN context. Third, the study draws on the empirical results to derive actionable policy implications for FDI governance, energy transition, and industrial planning that can help reconcile manufacturing-led growth with ASEAN's Net-Zero commitments.

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2. METHOD

2.1. Data and sample construction

The empirical analysis focuses on eight ASEAN economies: Brunei, Cambodia, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. These countries were selected because they share geographical proximity and deep economic integration, account for the bulk of regional manufacturingoriented FDI inflows, and have all articulated explicit climatechange mitigation commitments. Lao PDR and Myanmar are not included because consistent sectoral data on manufacturing FDI and CO_2 emissions for 2005–2022 are either missing or highly incomplete in the main international databases, which prevents the construction of a balanced and reliable panel.

Annual data for manufacturing sector CO_2 emissions, FDI inflows, real GDP per capita, total population, and the share of fossil fuels in total energy consumption were compiled from the World Bank's World Development Indicators and UNCTADstat. Following standard cleaning procedures, observations with missing or inconsistent values were removed, yielding a balanced panel of 144 country-year observations (8 countries × 18 years), which satisfies conventional samplesize recommendations for panel regression (Long & Freese, 2001; Green, 1991). All monetary variables are converted into constant prices where relevant, and variables are expressed in logarithms or percentages to enhance comparability and reduce scale heterogeneity across countries.

2.2. Model specification

The empirical model builds on the Environmental Kuznets Curve framework and FDI–emissions literature to explain manufacturing CO_2 emissions (Thu, 2023; Wang et al., 2023; Febriyanto et al., 2024; Nguyen et al., 2023). We estimate the following linear panel specifications:

$$\ln CO2_{it} = \alpha_i + \beta_1 FDI_{it} + \beta_2 \ln CO2_{i,t-1} + \beta_3 GDPPC_{it} + \beta_4 GDPPC_{it}^2 + \beta_5 \ln POP_{it} + \beta_6 FFEC_{it} + \varepsilon_{it}, \quad (1)$$

where i indexes countries and t denotes years. Here, $\ln CO2_{it}$ is the natural logarithm of manufacturing sector CO_2 emissions; FDI_{it} measures inward foreign direct investment inflows adjusted for the manufacturing share in GDP; $GDPPC_{it}$ and $GDPPC_{it}^2$ capture potential nonlinear (EKCtype) effects of income; $\ln POP_{it}$ is the logarithm of total population; and $FFEC_{it}$ denotes the share of fossil fuel energy consumption in total energy use. The countryspecific intercept α_i absorbs timeinvariant heterogeneity such as geography and baseline industrial structure, while ε_{it} is the idiosyncratic error term.

The selection and measurement of variables follow prevailing empirical practice in studies of FDI and environmental quality, aiming to capture the main economic, demographic, and energyrelated drivers of manufacturing emissions.

2.3. Empirical procedure and estimation strategy

The empirical procedure was conducted in four steps. First, we summarize the data using descriptive statistics and pairwise correlation coefficients to characterize the distribution of manufacturing CO_2 emissions, FDI inflows, income, population, and fossil fuel dependence across countries and over time. Second, we conduct standard panel diagnostics, including tests for crosssectional dependence, unit roots, and cointegration, to determine the integration properties of the variables and the presence of any longrun equilibrium relationships.

Third, we estimate pooled ordinary least squares, fixedeffects, and randomeffects models to obtain baseline coefficient estimates and then use the Hausman test to select between the fixedeffects and randomeffects specifications. Additional diagnostics, such as the Breusch–Pagan and Wooldridge tests, are applied to detect heteroscedasticity and serial correlation in the error structure. Finally, given evidence of heteroscedasticity and autocorrelation in the preferred randomeffects model, we employ feasible generalized least squares (FGLS) as the main estimator to obtain more efficient and robust parameter estimates for the determinants of manufacturing CO_2 emissions.

3. RESULTS

Table 1 reports the descriptive statistics of the variables used in this study. Manufacturing CO_2 emissions (in logs) showed a moderate mean level and sizeable dispersion, indicating substantial differences across countries and over time. FDI inflows, per capita income, and population also exhibit wide variation, reflecting the coexistence of low and highincome, small and large economies within ASEAN. The fossil fuel share in total energy consumption is high on average, with most countries still heavily reliant on coal, oil, and gas, despite some recent movement toward renewable sources. Overall, the descriptive statistics point to marked heterogeneity in industrial scale, development level, and energy structure, which motivates the use of panel techniques to identify the main drivers of manufacturing CO_2 emissions in the region.

Table 2 reports the correlation matrix for the main variables, providing preliminary insights into their relationships. Manufacturing CO_2 emissions are strongly and significantly correlated with their own lag, indicating considerable temporal persistence in sectoral emissions. Population (in logs) is also highly and positively associated with CO_2 emissions, consistent with the fact that larger, more populous economies tend to host more manufacturing activity and thus emit more.

FDI inflows display a moderate, positive, and statistically significant correlation with manufacturing emissions (0.227), suggesting that higher foreign investment is, on average, linked to higher sectoral CO_2 output, although the strength of this association varies across countries and over time. Per capita income shows a negative correlation with emissions but a positive association with both FDI and fossil fuel energy use, a pattern that is broadly consistent with Environmental Kuznets Curve considerations. Fossil fuel energy consumption is positively correlated with emissions and strongly related to income, underlining the continued reliance of economic expansion on fossil fuels in this region. Overall, the correlation matrix points to a dense set of links between development, FDI, energy structure, and environmental outcomes, which motivates the multivariate panel regressions in the next section.

Table 1. Descriptive statistics

Variable	Number of observations	Average	Standard deviation	Minimum	Maximum
CO2	144	2.904807	1.940082	–1.822013	5.288802
FDI	144	2.98369	4.502203	–1.605897	27.83306
CO_{2t-1}	144	2.849582	1.977159	–1.982678	5.288802
GDPPC	144	14.29484	19.48437	0.5257973	88.4287
$GDPPC^2$	144	3.598426	2.626441	–1.285679	8.964393
POP	144	17.04249	1.935513	12.79084	19.44611
FFEC	144	78.36847	20.3451	24.44	100

Table 2. Correlation matrix

Variable	CO2	FDI	CO_{2t-1}	GDPPC	$GDPPC^2$	POP	FFEC
CO2	1.0000						
FDI	0.2270 (0.0062)	1.0000					
CO_{2t-1}	0.9931 (0.0000)	0.2271 (0.0062)	1.0000				
GDPPC	–0.2953 (0.0003)	0.7027 (0.0000)	–0.2843 (0.0006)	1.0000			
$GDPPC^2$	–0.1810 (0.0299)	0.5151 (0.0000)	–0.1642 (0.0493)	0.8916 (0.0000)	1.0000		
POP	0.7992 (0.0000)	–0.0718 (0.3925)	0.7890 (0.0000)	–0.6946 (0.0000)	–0.6888 (0.0000)	1.0000	
FFEC	0.1920 (0.0212)	0.3506 (0.0000)	0.2098 (0.0116)	0.6088 (0.0000)	0.8426 (0.0000)	–0.3959 (0.0000)	1.0000

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Summary results for crosssectional dependence, unit root, and cointegration tests are reported in Appendix A, Tables A1–A3. The crosssectional dependence test indicates that all variables, including log CO_2 emissions, FDI, lagged emissions, income, population, and fossil fuel use, exhibit significant crosssectional correlation, pointing to the presence of common shocks and spillovers across ASEAN economies. This supports the use of panel methods that allow for correlated errors.

The panel unit root (CIPS) test distinguishes between variables that are stationary in levels and those that become stationary only after first differencing. CO_2 emissions, population, and fossil fuel energy consumption are found to be stationary at levels, whereas FDI, GDP per capita, and its squared term are integrated of order one. The lagged CO_2 variable, which is constructed from the same series as CO_2, shows a CIPS statistic of –2.207 at level, marginally below the 5% critical value of –2.33; given that CO_2 itself is stationary (CIPS = –2.706), the lag is treated as stationary in the subsequent analysis. These integration properties are considered when specifying empirical models.

Finally, the cointegration test does not provide evidence of a stable longrun equilibrium relationship among the variables, as the null of no cointegration cannot be rejected at conventional significance levels. This outcome justifies focusing on short and mediumrun dynamics and supports the use of pooled OLS, fixedeffects, randomeffects, and FGLS estimators in the subsequent regression analysis.

The pooled OLS regression results are reported in Table 3 and provide an initial benchmark using 136 country–year observations. The specification includes FDI inflows, lagged emissions, income and its square, population, and fossil fuel consumption as determinants of manufacturing CO_2 emissions. The model exhibits very high explanatory power, indicating that these covariates jointly account for almost all of the observed variation in emissions. FDI, lagged emissions, population, and fossil fuel use all entered with positive and statistically significant coefficients, suggesting that foreign investment, emission persistence, demographic scale, and reliance on fossil fuels are associated with higher manufacturing emissions. In contrast, GDP per capita and its squared term are not significant, offering no support for an Environmental Kuznets Curve pattern in this sample. Overall, the pooled OLS estimates highlight the importance of economic scale, capital flows, and energy structure in manufacturing emissions. However, this specification does not correct for unobserved heterogeneity or serial correlation, which motivates the use of panel estimators in the next step.

Table 3. Pooled OLS model regression results

Variable	Coefficient	Std. Error	P-value
FDI	0.0440***	0.0090	0.000
$dCO2_{t-1}$	0.4790***	0.1437	0.001
dGDPPC	–0.0119	0.0186	0.524
dGDPPC ^{2}	0.3961	0.2551	0.123
POP	1.0223***	0.0198	0.000
FFEC	0.0550***	0.0021	0.000
CONS	–19.0194***	0.4181	0.000
Number of observations		136	
F(6, 129)		517.33	
Prob > F		0.0000	
R-squared		0.9601	

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

Multicollinearity is not a concern, as average variance inflation factors remain well below conventional thresholds. In contrast, diagnostic tests for heteroscedasticity and serial correlation in the pooled OLS residuals reject the assumptions of constant variance and no autocorrelation. Detailed results are reported in Appendix A, Tables A4-A5, and motivate the use of panel estimators that explicitly account for these errorstructure issues.

Table 4 reports the fixedeffects and randomeffects estimates for manufacturing CO_2 emissions. In both specifications, FDI, lagged emissions, and fossil fuel consumption display positive and statistically significant coefficients, indicating a robust association with higher sectoral emissions. The randomeffects model achieves substantially higher explanatory power (*R*squared = 95.63%) than the fixedeffects specification (*R*squared = 22.28%).

Table 5 presents the Hausman test used to choose between the fixed and randomeffects specifications. The test statistic is not significant, so the null hypothesis that the randomeffects estimator

Table 4. Regression results of FEM and REM models

Variable	FEM model		REM model	
	Coefficient	P-value	Coefficient	P-value
FDI	0.0241**	0.048	0.0188*	0.091
$dCO2_{t-1}$	0.4135***	0.000	0.4412***	0.000
dGDPPC	0.0013	0.930	–0.0002	0.986
$dGDPPC^2$	0.1349	0.526	0.2296	0.253
POP	0.2038	0.685	0.9951***	0.000
FFEC	0.0631***	0.000	0.0579***	0.000
CONS	–5.6056	0.502	–18.6861***	0.000
Number of observations	136		136	
R-squared	22.28%		95.63%	
Prob > F	0.0000		0.0000	

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

is consistent cannot be rejected. Accordingly, the randomeffects model is preferred as the more efficient specification for this dataset.

Table 5. Hausman test results

Hausman test	
Value of chi2(6)	2.82
p-value (Prob > chi2)	0.8314

Finally, Table 6 reports diagnostic tests for the randomeffects specification. Both the Breusch–Pagan test for heteroscedasticity (p-value = 0.0000 < 0.05) and the Wooldridge test for serial correlation (p-value = 0.0000 < 0.05) strongly reject the classical assumptions, indicating heteroscedastic and autocorrelated errors. To address these issues and enhance the reliability of the estimates, this study employs feasible generalized least squares (FGLS).

Table 6. REM model defect inspection results

Breusch–Pagan test	
chibar2(01) value	166.80
Prob value > chibar2	0.0000
Wooldridge test	
F(1, 7) value	143,116
p-value (Prob > F)	0.0000

Given the evidence of heteroscedasticity and serial correlation in the randomeffects specification, the model is reestimated using feasible generalized least squares (FGLS) to obtain more efficient and reliable coefficients in a panel setting typical of crosscountry environmental studies. Table 7 reports the FGLS results for manufacturing CO_2 emissions in ASEAN over 2005–2022.

Table 7. Model estimation results according to FGLS

Variable	Coefficient	Std. Error	P-value
FDI	0.0180***	0.0058	0.002
$dCO2_{t-1}$	0.0189	0.0646	0.770
dGDPPC	–0.0053	0.0056	0.348
$dGDPPC^2$	0.1014	0.0682	0.137
POP	0.9389***	0.0380	0.000
FFEC	0.0527***	0.0030	0.000
CONS	–17.2653***	0.8180	0.000
Number of observations		136	
Prob > chi2		0.0000	

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

The model is strongly significant overall (Prob > chi^2 = 0.0000), and three variables emerge as robust positive drivers of emissions: FDI inflows, population size, and fossil fuel energy consumption. The FDI coefficient (0.0180, $p < 0.01$) indicates that greater foreign investment is associated with higher CO_2 emissions, consistent with pollutionhaventype mechanism; the large population coefficient (0.9389, $p < 0.01$) highlights the role of demographic scale; and fossil fuel energy consumption (0.0527, $p < 0.01$) underscores the centrality of fossil fuel dependence. By contrast, lagged emissions and income variables are not statistically significant, suggesting neither strong persistence nor clear Kuznetstype nonlinearity in this specification. Overall, the FGLS estimates point to the need to improve the environmental quality and sectoral composition of FDI, manage populationdriven industrial expansion, and accelerate the shift away from fossil fuels toward cleaner energy sources in ASEAN.

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4. DISCUSSION

The FGLS estimates indicate that FDI inflows are positively associated with manufacturing CO_2 emissions (coefficient = 0.018, $p < 0.01$). This result is broadly consistent with the pollution haven hypothesis and aligns with several prior studies, although important differences in magnitude and scope deserve attention. For instance, Febriyanto et al. (2024) used country-specific ARDL models for four ASEAN economies from 1990 to 2020 and found that FDI had a positive short-term effect on CO_2 emissions in Singapore and Indonesia and a positive long-term effect in Vietnam and Singapore, but no significant impact in Malaysia. In contrast, the present study uses a panel framework covering eight ASEAN countries and focuses explicitly on manufacturing sector emissions rather than total CO_2 emissions. The consistently positive and significant FDI coefficient obtained here suggests that, when the analysis is restricted to the manufacturing sector and pooled across the region, the emission-increasing effect of FDI is more uniform than the country-by-country ARDL approach would indicate. One possible explanation is that panel estimation averages out idiosyncratic country effects, while the ARDL approach captures heterogeneous short- versus long-run dynamics that a static panel cannot isolate. Nguyen et al. (2023), applying the GMM method to ASEAN data for 2000–2019, similarly reported that FDI increases environmental pollution. However, their study emphasized the moderating role of institutional quality, finding that stronger governance significantly reduced the adverse environmental impact of FDI. This study does not include institutional variables, which may partly explain why the FDI coefficient is unconditionally positive. Future extensions incorporating governance indicators could help assess whether the pollution haven pattern observed in this study weakens in countries with stronger regulations.

In addition, Susilawati and Satrianto (2024) used two-stage least squares (2SLS) for ASEAN-5 from 2000 to 2020 and found a larger FDI coefficient on CO_2 emissions (0.082, $p < 0.05$). The difference in magnitude, the present study's coefficient (0.018) versus Satrianto's (2024) coefficient (0.082), can be attributed to at least two factors. First, their model estimates the effect of FDI on total CO_2, whereas the present study isolates manufacturing emissions, which represent only a subset of total emissions. Second, 2SLS addresses simultaneity but may produce larger coefficients if the instruments are strong, whereas FGLS addresses heteroscedasticity and serial correlation without instrumentation. In contrast, Shaari et al. (2014), using FMOLS and Granger causality tests for 15 developing countries from 1992 to 2012, found no significant effect of FDI on CO_2 emissions in the long run or short run. Similarly, Gunarto (2020) reported that the long-run FDI coefficient was insignificant in a sample of Asian states from 1970 to 2014. These null findings likely reflect the broader, more heterogeneous country samples and time periods used in those studies, which mix economies at very different stages of industrial development. The present study's focus on ASEAN manufacturing, a relatively homogeneous group of middle-income economies with high shares of FDI directed toward industry, provides a setting where the emission-increasing effect of FDI is more likely to emerge and be statistically detectable.

A comparison with single-country evidence for Vietnam is also instructive. Nam et al. (2023) applied the ARDL approach for Vietnam over 1990–2018 and estimated a long-run FDI elasticity of 0.190 ($p < 0.05$) on total CO_2 emissions. However, the short-run FDI effects are negative, with lagged coefficients of −0.112 and −0.060. This pattern suggests that technology transfer associated with new FDI temporarily reduces emissions before capacity expansion drives them upward. Thu (2023) also found that technology transfer linked to FDI reduces greenhouse gas emissions in Vietnam. These findings point to time-horizon dynamics that the present panel specification cannot fully disentangle, which captures a pooled contemporaneous association. The positive FDI coefficient in our FGLS model likely reflects the net long-run emission-increasing effect of FDI across the region, consistent with Nam et al. (2023). The short-run emission reductions documented in Vietnam may be obscured in the regional panel, as the pooled estimation captures the average contemporaneous association rather than country-specific dynamic adjustments.

For a wider scale, Wang et al. (2023) used a panel threshold model for 67 countries spanning a wide range of income levels and demonstrated that FDI increases CO_2 emissions when GDP per capita is below approximately USD 542 (corresponding to the poorest low-income economies), while the effect turns negative only at very high income levels above USD 46,515. Given that most ASEAN economies in our sample have per-capita incomes well above the lower threshold but far below the upper one, the present finding of a positive FDI–emissions link is fully consistent with Wang et al.'s (2023) threshold framework. This further reinforces the conclusion that ASEAN's current income levels are not high enough to enable the clean-technology benefits of FDI to outweigh its scale and composition effects.

Population size is the strongest driver of manufacturing emissions in the FGLS model (coefficient = 0.939, $p < 0.01$), a near-proportional relationship. This result aligns closely with that of Susilawati and Satrianto (2024), who reported a population coefficient of 1.306 for total CO_2 in ASEAN-5. The slightly lower magnitude in the present study may reflect the manufacturing-specific focus, as population growth also drives emissions in the transport, residential, and agricultural sectors, which are excluded here. However, both results confirm that demographic scale is a dominant structural driver of emissions in ASEAN. The near-proportional population–emissions elasticity is also consistent with the broader environmental economics literature. Thu (2023) and Wang et al. (2023) documented significant positive effects of population on emissions in their respective samples. This finding has direct implications for ASEAN policy. Without corresponding improvements in manufacturing energy efficiency and technology, continued population growth in countries such as Indonesia, Vietnam, and the Philippines will result in higher sectoral emissions.

Fossil fuel energy consumption has a strong and highly significant positive effect on manufacturing emissions (coefficient = 0.053, $p < 0.01$). Countries that rely more heavily on coal, oil, and gas for industrial energy systematically record higher emission levels, even after controlling for FDI, income, and population. This finding is consistent with the empirical literature. Gunarto (2020) reported that energy consumption was the primary determinant of CO_2 emissions in Asian states, with a significant positive coefficient, whereas FDI itself was not significant. Susilawati and Satrianto (2024) found that energy intensity had a significant positive effect on CO_2 emissions (coefficient = 0.343) in ASEAN-5, and that renewable energy consumption had a significant negative effect (–0.051). The magnitude of the fossil fuel coefficient in the present study (0.053) is comparable to the renewable energy coefficient in Susilawati and Satrianto's (2024) work (–0.051). This suggests that both the share of fossil fuel use and the adoption of renewable energy exert effects of similar magnitude on emissions, but in opposite directions. Importantly, the present result reinforces the conclusion that fossil fuel dependence is a more fundamental constraint on emission reduction than FDI. While FDI governance can be improved to shift investment toward cleaner sectors, the structural reliance on fossil fuels in ASEAN's energy mix remains the most powerful lever for meaningful emissions reduction.

The lagged CO_2 variable enters the FGLS model with a positive but statistically insignificant coefficient (0.019, $p = 0.770$), suggesting that interannual emission persistence is weak once structural factors (FDI, population, fossil fuel use) are accounted for. This finding contrasts with the pooled OLS and random-effects models estimated earlier in this paper, in which the lagged term was significant. The loss of significance under FGLS indicates that the apparent persistence in simpler models was likely an artifact of unmodeled serial correlation in the errors. Once FGLS corrects for this issue, the lagged term no longer contributes additional explanatory power. This result differs from Nam et al. (2023), who found lagged CO_2 significant at the 10% level in their ARDL specification for Vietnam. However, the ARDL approach by design emphasizes dynamic lag structures, whereas the present panel model prioritizes cross-country variation and error structure robustness. The practical implication is that short-term policy interventions, such as sudden changes in energy prices, environmental regulations, or investment screening criteria, can alter manufacturing emissions relatively quickly, without being constrained by strong path dependence.

GDP per capita and its squared term are both insignificant in the FGLS model, providing no support for an inverted-U (EKC) relationship be-

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tween income and manufacturing emissions in ASEAN. This result is consistent with Febriyanto et al. (2024), who also found no clear EKC pattern in their ASEAN sample, and with growing skepticism in the literature about the universality of the EKC, particularly in middle-income, manufacturing-dependent economies. Wang et al. (2023) demonstrated that the income threshold at which FDI begins to reduce emissions (USD 46,515) is far above the per capita income levels in most ASEAN countries, which helps explain why neither income level nor its quadratic term contributes to emission reduction in this sample. In contrast, Nam et al. (2023) found that GDP per capita is a highly significant predictor of CO_2 emissions in Vietnam (long-run elasticity = 1.562). This difference likely arises because Nam et al. (2023) used total CO_2 per capita as the dependent variable over a long period of rapid income growth (1990–2018), capturing the scale effect of development in all sectors. The present study's focus on manufacturing CO_2 across a panel of countries at varied income levels may mask country-specific income–emission dynamics that a single-country time-series approach can detect.

The absence of EKC evidence reinforces the argument that income growth alone will not automatically reduce manufacturing emissions in ASEAN. Deliberate policy actions, not simply economic development, are required to decouple industrial growth from carbon output.

CONCLUSION

This study examines how foreign direct investment (FDI), along with economic and demographic factors, affected manufacturing CO_2 emissions in eight ASEAN economies from 2005 to 2022. The empirical results demonstrate that higher FDI inflows, larger population sizes, and greater fossil fuel dependence significantly amplify manufacturing carbon emissions, whereas the effects of per capita income and historical emissions are not statistically significant. These findings indicate that foreign capital currently exacerbates regional environmental pressures, consistent with the pollution haven hypothesis, rather than generating a cleantechnology halo effect. Consequently, it can be concluded that, in the absence of stronger policy action, FDIdriven industrialization risks locking ASEAN countries into highcarbon development paths that undermine their longterm NetZero ambitions. To align industrial growth with sustainability, ASEAN governments should reorient their policy frameworks by enforcing stricter environmental standards for FDI approvals, providing incentives for green technology adoption, accelerating the shift toward renewable energy, and integrating emission constraints into industrial spatial planning. Given that the analysis is constrained by data availability and country coverage, future research should extend the temporal and regional scope and incorporate richer indicators of institutional quality, energy structure, and technology adoption.

AUTHOR CONTRIBUTIONS

Conceptualization: Quoc Tran-Nam.
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Formal analysis: Quoc Tran-Nam.
Funding acquisition: Quoc Tran-Nam.
Investigation: Nhi Tran.
Methodology: Quoc Tran-Nam, Nhi Tran.
Project administration: Quoc Tran-Nam.
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Supervision: Quoc Tran-Nam.
Validation: Nhi Tran.
Visualization: Nhi Tran.
Writing – original draft: Nhi Tran.
Writing – review & editing: Quoc Tran-Nam.

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APPENDIX A

Table A1. Pesaran's CD test results

Variable	Pesaran CD Statistic	Prob.
CO2	6.380737	0.0000
FDI	6.420649	0.0000
$CO2_{t-1}$	7.598601	0.0000
GDPPC	15.10336	0.0000
$GDPPC^2$	15.70054	0.0000
POP	22.00692	0.0000
FFEC	–2.424705	0.0153

Table A2. Pesaran panel unit root test results

No.	Variable	Level (CIPS)	First-order differential (CIPS)	Conclude
1	CO2	–2.706		I(0)
2	FDI	–1.938	–3.895	I(1)
3	$CO2_{t-1}$	–2.207	–4.214	I(1)*
4	GDPPC	–0.742	–3.183	I(1)
5	$GDPPC^2$	–1.360	–2.654	I(1)
6	POP	–3.187		I(0)
7	FFEC	–2.707		I(0)
Critical values (10%; 5%; 1%) = –2.18; –2.33; –2.64				

Note: *CO_2t–1 reports a CIPS statistic of –2.207, marginally below the 5% critical value of –2.33. As CO_2 itself is stationary (CIPS = –2.706), CO_2t–1 is treated as I(0) in the subsequent analysis; see Results section for discussion.

Table A3. Westerlund test results

	Westerlund test	
Variance ratio	Statistics	p-value
	–0.7810	0.2174

Table A4. Multicollinearity test results

Variable	VIF	1/VIF
dGDPPC	2.66	0.375932
$dGDPPC^2$	2.23	0.448804
FDI	1.53	0.652332
FFEC	1.52	0.657790
POP	1.31	0.765765
$dCO2_{t-1}$	1.06	0.947161
Average VIF	1.72	

Table A5. Pooled OLS model defect testing results

White test	
Value of chi2(27)	56.39
p-value (Prob > chi2)	0.0008
Wooldridge test	
F(1, 7) value	143,116
p-value (Prob > F)	0.0000

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