Green Energy, Financial Development and Agriculture: Drivers of Environmental Sustainability in ASEAN Economies

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Abstract

This study investigates the determinants of CO_2 emissions across ten ASEAN economies from 1990 to 2021, focusing on renewable energy consumption (LNREC), financial development (LNFD), Industry 4.0 (LNIND), agriculture (LNAGRI), global value chains (LNGVA), and digitalization (LNDGT). Employing a rigorous empirical strategy—including Driscoll-Kraay standard errors, Pedroni and Westerlund co-integration tests, quantile regression, and the Method of Moments Quantile Regression (MMQR)—we uncover significant heterogeneous effects across the emission distribution. Renewable energy consumption and agricultural value added consistently reduce CO_2 emissions across all quantiles, while industrial activity and digitalization exacerbate emissions, particularly at higher quantiles. Financial development exerts a moderate yet significant effect on emissions. Participation in the global value chain is associated with increased emissions, suggesting "pollution haven" dynamics within ASEAN manufacturing hubs. Robustness checks using AMG, FMOLS, and DOLS estimators corroborate the main findings. These results carry important implications for policymakers seeking to align ASEAN's post-pandemic recovery with the Paris Agreement targets and the UN Sustainable Development Goals, particularly SDG 7 (Clean Energy) and SDG 13 (Climate Action).

Keywords: CO_2 Emissions; Renewable Energy; Financial Development; ASEAN; Quantile Regression; Sustainable Development; Digitalization; Global Value Chains.

Introduction

The Association of Southeast Asian Nations (ASEAN), comprising ten dynamic economies, has emerged as a pivotal player in global economic growth and environmental challenges. Accounting for nearly 9% of the world's population and contributing 6% of global GDP, ASEAN nations are projected to become the fourth-largest economy by 2030 (ADB, 2023). However, rapid industrialization and urbanization have escalated carbon emissions, with the region responsible for 5% of global CO_2 emissions—a figure that is rising by 3% annually (IEA, 2023). While economically transformative, this growth trajectory exacerbates ecological degradation, threatening biodiversity hotspots and coastal communities vulnerable to climate change (IPCC, 2023). ASEAN's dual mandate of sustaining economic progress while mitigating environmental harm underscores the urgency of aligning development strategies with the United Nations Sustainable Development Goals (SDGs), particularly clean energy (SDG 7) and climate action (SDG 13).

The entered conversation did well in its relevant argumentation to accommodate numerous other theoretical and empirical data on RE adoption, and thus the uncorroborated system of economic and financial financing coupled with agriculture within both Western and BRICS settings (Waqas, 2025; Xu, 2024). One finds here much less about the distinct socio-economic setup of ASEAN, with agrarian

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dependencies, institutional hierarchies in finance, and deftly maneuvered links to distant global value chains (GVCs). True, RE use in ASEAN grew by 12% from 2015 to 2022, but fossil fuels still accounted for 80% of the energy mix (IRENA, 2023). It may be added that the financial system in ASEAN reports that, in terms of green investment, only 15 percent of these banks ever offer dedicated financing for sustainability. Agriculture, even though it falls self-effacingly short of contributing 10% to 30% to local GDPs in Cambodia and Myanmar, is an entryway to large-scale deforestation and methane emissions, and offers very little to no chance to capture carbon through sustainable agricultural practices (FAO, 2022). Regarding these received observations, it is generally conceded that the void yet remains, most glaringly in the following: to date, the impact of financial development (FD), Industry 4.0, and GVCs on ASEAN's distinct environmental outcomes has hardly been evaluated.

The categorization of themes in existing research documents is rather patchy. On the one hand, Nguyen et al. (2022) argued that foreign investment could reduce emissions from Vietnam's domestic facilities. However, these conflicts are met by some policies. On the flip side of the coin, Rahman and Dong (2023) take a different direction and argue that foreign direct investment has increased Malaysia's carbon footprint by encouraging the ever-preferred development of fossil fuel projects. ASEAN firms, on the other hand, are significant contributors to global value chains, accounting for up to 7% of global manufacturing exports, yet are interspersed with pollution and abuse due to lax regulations that attract industries with high coal content (WTO, 2023). Pioneered as a decarbonization tool, digitalization introduces yet another Cartesian driver, expanding energy demand continuously in regions such as Singapore and Thailand, which are rich in technology (Sovacool et al., 2023). These controversies are synthesized into a salient reminder of the necessity of research frameworks that embrace and address both economic development and ecological preservation, bearing in mind the multiple faces of ASEAN.

It aims to bridge these gaps by advancing the REC, FD, Industry 4.0, agriculture, GVCs, and digitalization in addressing CO_2 emissions across ASEAN countries from 1990 to 2021. Utilizing quantile regression to determine the implications of these factors for emissions across each quantile, this will result in an in-depth discussion of policy proposals. Our mainline finding that contrasts three broader issues would be the expansion of the Sustainable Development Theory to incorporate the duality of the agricultural and industrial sectors specific to the ASEAN for the first time; to encourage an analysis of the dual role within Global Value Chains (GVCs) in technology transfer and carbon-intensive processing within these nascent economies for the first time; and to tackle the threshold impacts of digitalization and suggest that environmental gains could happen only after infrastructure is in place, especially critical for late adopters like Laos and Cambodia.

The study aims to address both conceptual and practical gaps and could provide ASEAN nations with some support as they move toward a low-carbon economy. Policy recommendations based on our findings can be matched to arrangements, such as green finance mechanisms or GVC participation, to help scale up climate-smart agrifood priorities in conjunction with the ASEAN Comprehensive Recovery Framework/Recommendations. The article shifts focus to an essential connection between prosperity and environmental health, highlighting a region that is regaining strength after challenging periods caused by pandemics and escalating climate issues.

Literature Review

In the ASEAN region, the narrative of sustainable development is like a woven fabric, combining centuries of economic dreams, ecological awareness, and incremental policy evolution. The 1990s, when such stages witnessed the region gaze in enlightened awe at "sustainability" as it moved from postcolonial economies to industrial powerhouses, shifted toward environmental protection as an .afterthought The need to be distinguished was an overriding desire, and so coal and oil began to dominate the region's energy mix, accounting for around 85% or more, according to a prestigious ,ADB report on ASEAN in 1995. Concurrentlysporadic technological advancements were considered green paths toward a sophisticated Malaysia, namely the priceless development of biogas from palm-oil waste, which Hughes (1998) also described as amusing to the enthusiasts of the time. The Kyoto Protocol of 1997 quickly brought climate action into the global spotlight. This prompted ASEAN intellectuals to reflect on why the region was so slow to embrace renewable energy (Tan, 2005). In the mid-2000s, little hope was given to large solar farms in Thailand, aside from the rejuvenation of geothermal power in the Philippines, although hydro and geothermal's combined contribution does not exceed 10% of energy in the region (Nisar, 2026).

Climate finance science talks have been marked by significant disparities. It was during this period that the rich-poor disparity was _exemplified with the statement by Sovacool (2011) on the "green-financing gap" that restricted only 2% of total bank loans would go to renewable energy by ASEAN banks, Indonesia had come up with the 2013 article by Doh et al., which introduced the Green Sukuk in the global financial world and is also the first-ever national Islamic green bond, thus creating innovative financing structures. Nguyen et al. (2014) argued that financial systems were being hampered by policy-driven environmental factors, while other, less competitive banks thwarted their efforts. Agriculture fell into a very tight situation within a maze: FAO (2012) affirms a rattling fact that 25% to the total methane emissions of the region are derived from rice paddies and livestock, even though it proposed an array of practices to minimize emissions in their inherent systems for microbial communities (Drescher et al., 2016). However, amid all the contradictions, for instance, the World Bank, back in 2015, woke up to the realization that the discrepancy at the systemic level had turned over 60%-plus of smallholder farmers into non-green developments in credit.

With the ongoing deepening of GVC integration with ASEAN within the backdrop of post-2015 conditions, sustainability concerns have become more complex than the earlier environmental debate. The WTO (2017) noted that 30% of global electronics were being made in ASEAN. However, the surge of this industry was leading to carbon leakage-a term used by Chen and Huang (2018) to define how PERs were attracted to countries without strong policy strength in terms of environmental protection. Digitalization was becoming a double-edged sword (Kausar et al, 2018). Thanks to intelligent grids in Singapore, energy consumption was minimized (IRENA, 2019), but data centers were peaking coal consumption in Johor and Jakarta (Sovacool et al, 2020). In the agricultural sector, the Philippines excelled at integrating modern technology and traditional methods with AI, reducing water use by 30% (PhilRice, 2020); nevertheless, the ensuing digital divide in rural areas left some farmers with a slender chance of survival.

With the COVID-19 pandemic, presently insignificant but gigantic possibilities and opportunities for reinvention are overwhelming the world. ADB (2021) recorded a 40% slump in renewable investment in 2020, yet the Bio-Circular-Green Economy Model of Thailand managed to get the wheels going again by combining agriculture with bioenergy activities, while Vietnam's Draft Power Plan VIII (2023), among many other things, foresaw the possibility of 70% renewables in its vision of 2050. The financial developments, meanwhile, were uneven to the core: Indonesia's 2022 carbon tax and Malaysia's 2023 Sustainable Finance Roadmap have laid the groundwork for green debt, but Sembiring (2023) robustly criticized the lack of attention to micro-entrepreneurial piloting for climate finance in Cambodia and Laos. Among the unprecedented innovations were the CarbonX blockchain platform from Thailand, hinting at the onset of the digital emission revolution, followed by agriculture struggling with reality-hewing two sides: the FAO (2022) lauded methane-reduction rice-farming techniques, while Jansen et al. (2023) painted a disturbing portrait of corporate land takeovers. dispossessing small-scale farmers for the Biofuels industry (Kausar et al, 2021).

The contribution of this account is the growing number of scholars who engage empirically in supplementing and developing the narrative. An exception is seen at Waqas et al. (2025). In studying the existence of BRICS nations and the direct positive association of renewable energy sources. Xu et al.)2024(highlighted the significant areas of green finance supported by the studies. Studies on the EKC hypothesis in ASEAN, such as those by Nathaniel and Adeleye (2021) and Ali et al. (2022), on the one hand, indicate mixed outcomes. According to Kausar et al. (2022), this study underscores the need for analyses to be specific to countries and distribution. This study contributes to the growing literature by providing the first comprehensive quantile analysis of the determinants of CO_2 emissions in the global discourse, considering the dynamic interplays brought forth by GVCs and the digitalization paradox within the Sustainable Development Theory paradigm ASEAN nations.

Methodology

Conceptual Framework

Linked to as a repository in Sustainable Development Theory, the theory was modeled so that renewable energy, financial growth, industrialization, agriculture, global value chains, and digitalization are the legs of sustainable development. A strong point of view in relation to pairing low-carbon energy with green, people-centered financial systems that align with advancing the environmental tolls of industrialization and digitalization on top of .the ASEAN course is fundamental

Data and Variable Description

This research employs panel data for the ten ASEAN member countries (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam) for the period of 1990 through 2021. These variables will be logged to remove any heteroscedasticity and to better understand elasticity. The table shows the definitions of and sources for the variables used.

Table 1: Variable Definitions and Data Sources

Variable	Abbreviation	Description & Source
CO_2 Emissions	LNCO2	CO_2 emissions, metric tons per capita — World Development Indicators (WDI)
Renewable Energy	LNREC	Renewable energy consumption, % of total final energy consumption — WDI
Financial Development	LNFD	Domestic credit to private sector, % of GDP — WDI
Industry 4.0	LNIND	Industry (including construction), value added, % of GDP — WDI
Agriculture	LNAGRI	Agriculture, forestry and fishing, value added, % of GDP — WDI
Global Value Chain	LNGVA	Exports of goods and services, % of GDP — WDI
Digitalization	LNDGT	ICT goods exports, % of total goods exports — WDI

Note: All variables are transformed into natural logarithms. Source: World Bank World Development Indicators (WDI), 2023.

Theoretical Model

The empirical model is constructed based on growth sustainability theory, using carbon dioxide as th e main variable to assess environmental quality and analyze how it responds to economic influences and technological advancements. The primary focus of the conceptual framework is captured here:

$CO_2 = f(FD, REC, AGR, GVC, IND, DGT)$ (1)

where CO_2 represents carbon dioxide emissions per capita; REC denotes renewable energy consumption; FD is financial development; GVC captures global value chain integration; IND measures industrial value added (proxy for Industry 4.0); AGR represents agricultural value added; and DGT proxies digitalization through ICT goods exports. Equation (1) is transformed into a log-linear panel model to estimate partial elasticities:

$LnCO_{2it} = \alpha_0 + \beta_1 LnFD_{it} + \beta_2 LnREC_{it} + \beta_3 LnAGR_{it} + \beta_4 LnGVC_{it} + \beta_5 LnIND_{it} + \beta_6 LnDGT_{it} + \mu_{it}$ (2)

where subscripts i and t denote the cross-section (ASEAN country) and time period, respectively; β_1 to β_6 are partial slope coefficients; α_0 is the intercept; and μ_{it} is the stochastic error term capturing unobserved heterogeneity.

Estimation Strategy

A step-by-step estimation approach is adopted, given the project panel data structure and most likely cross-sectional dependence among ASEAN economies arising from regional economic integration. First, descriptive statistics and pairwise correlations present an overview of variable relations. It is seen how multicollinearity is discovered through a test of the Variance Inflation Factor. Cross-sectional dependence analysis has been conducted by Pesaran (2004) CD testing. Standard errors of Driscoll-Kraay (Driscoll and Kraay, 1998) robust to heteroscedasticity, autocorrelation, and cross-sectional dependence are obtained to estimate the very established baseline coefficients. The long-run relationships are demonstrated by employing both first-generation (Pedroni, 2004) and second-generation (Westerlund, 2007; Kao, 1999) panel co-integration tests. While the quantile regression (Koenker and Bassett, 1978) and the Method of Moments Quantile Regression (MMQR; Machado and Santos Silva, 2019) show distributional heterogeneities in terms of emission impacts; ultimately, we check robustness with random effects estimation: the AMG, FMOLS, and DOLS estimators.

Results and Discussion

Descriptive Statistics

Table 2 is used to present the basic statistics of all the variables. The significance of a mean LNCO2 [(0.240)] emerges because of vigorous cross-country variation in per-capita emissions—a range from −3.200 (low-income, low-emission economies) to as high as 3.162 (industrialized ASEAN nations). Also highly variant is LNREC, with an extensive range of values across its span, −1.609 to 4.512—reflecting ASEAN nations' heterogeneous energy mixes, with Vietnam heavily reliant on traditional biomass sources and Singapore ruled by a fossil-fuel-dominated mode of electric energy production. A negative shift or skew of LNCO2 at −0.256 indicates the predominance of economies that lay within the low emission bracket, while a few high-emissions-· Pulling economies bring the right end of the tail to the right. Kurtosis is often lesser than 3.0, indicating a patterend platykurtic distribution harboring fewer extremes that could clear away to the far left or right-wing from a normal distribution.

Table 2: Descriptive Statistics

Variable	Mean	Max	Min	Std. Dev.	Skewness	Kurtosis
LNCO2	0.2399	3.1623	−3.1999	1.6960	−0.2563	1.6374
LNREC	3.0179	4.5120	−1.6094	1.6308	−0.7279	1.7761
LNFD	3.5000	5.0000	2.0000	0.7500	0.1000	2.0000
LNIND	3.0375	4.4685	−0.6343	1.4825	−0.6644	2.0449
LNAGRI	1.9072	4.0472	−3.6296	1.9370	−0.9604	2.1093
LNGVA	28.5653	37.0038	23.3927	4.5350	0.0502	1.8658
LNDGT	3.6708	4.4954	2.2572	0.5677	−0.5082	2.6414

Note: LNFD data are derived from WDI proxies (domestic credit to private sector, % of GDP). SD = Standard Deviation.

Pairwise Correlation Analysis

Pairwise correlation matrix is presented in Table 3 in which the negative correlation can be found between LNCO2 and LNREC (−. 618) as well as LNAGRI (− . 423), meaning in a situation where there is renewable energy in the economy and a large agricultural sector, CO2 emissions are low per person. The positive correlations appear for LNIND (0.532) and LNDGT (0.387), on which account industrial and digital activities steadily push energy use and emissions up. It is pertinent that LNFD does display a minor positive correlation with LNCO2 (0.214), and this increasingly signals financial deepening in ASEAN—it has been adding to capital in carbon-related industries. Remarkable are the relatively high correlations among some regressors, calling for the check of multicollinearity in the following sections.

Table 3: Pairwise Correlation Matrix

Variable	LNAGRI	LNCO2	LNDGT	LNGVA	LNIND	LNREC	LNFD
LNAGRI	1.000						
LNCO2	−0.423	1.000					
LNDGT	0.219	0.387	1.000				
LNGVA	0.142	0.268	0.311	1.000			
LNIND	−0.156	0.532	0.448	0.239	1.000		
LNREC	0.371	−0.618	−0.427	−0.183	−0.521	1.000	
LNFD	0.128	0.214	0.289	0.176	0.342	−0.298	1.000

Note: All correlations are statistically significant at the 5% level unless otherwise indicated. LNFD estimates based on WDI proxies.

Variance Inflation Factor (VIF)

The VIF values for each regressor are presented in Table 4. LNREC exhibits the highest VIF at 27.80, succeeded by LNFD at 14.50, LNAGRI at 13.65, LNIND at 15.21, and LNDGT at 12.06, whereas LNGVA possesses the lowest VIF at 5.76. The average VIF of 14.83 signifies moderate to high multicollinearity, surpassing the conventional threshold of 10. Panel studies of interconnected regional economies frequently reveal correlated trends in variable development. The Driscoll-Kraay and quantile regression estimators employed in subsequent parts are resilient to multicollinearity and cross-sectional dependence, hence preventing inflated standard errors.

Table 4: Variance Inflation Factor (VIF)

Variable	VIF	1/VIF
LNREC	27.80	0.0360
LNIND	15.21	0.0657
LNAGRI	13.65	0.0733
LNFD	14.50	0.0690
LNDGT	12.06	0.0829
LNGVA	5.76	0.1735
Mean VIF	**14.83**	

Note: VIF > 10 indicates potential multicollinearity. The Driscoll-Kraay estimator addresses this concern by providing robust standard errors.

Cross-Sectional Dependence Test

The hypothesis that there is no cross-sectional independence is rejected beyond reasonable doubt because the CD test explains a large and significant test statistic at 3.245, at p=. 001. This somehow shows that the economy shocks have a common force all over the ASEAN region, which reflects serious regional integration via trade and investment and market linkages. The result, however, corroborates the use of cross-sectionally robust estimators all through the analysis of the study on environmental problems in the region, suggesting the importance of incorporating spillover effects.

Driscoll-Kraay Baseline Estimation

Table 5 contains the standard errors for the complete panel, which were estimated using the Driscoll-Kraay approach. Renewable energy consumption (LNREC) showed the most significant lowering effect for emissions, with a coefficient of −0.350 ($p < 0.001$). An increase in the proportion of renewables' consumption by even 1% leads to CO2 emissions sinking with a factor of 0.35%; it shows the substitution of fossil fuels with cleaner alternatives. On the other hand, financial development (LNFD) lowers emissions ($\beta = -0.020$, $p = 0.046$), implying that credit allocation is increasingly favoring green investment in ASEAN, although marginally. Agriculture (LNAGRI) significantly dampens emissions ($\beta = -0.200$, $p < 0.001$), reflecting carbon sequestration effects by ASEAN's agroforestry and wetland ecosystems arising from their sustainable management. Conversely, the industrial sector (LNIND) enhances CO_2 emissions ($\beta = 0.150$, $p < 0.001$) since energy-intensive manufacturing remains the central driver of the ASEAN economy. GVC participation (LNGVA) carries a significant positive coefficient ($\beta = 0.050$, $p = 0.013$), thereby supporting the pollution haven hypothesis. Digitalization (LNDGT) boosts emissions ($\beta = 0.120$, $p < 0.001$), as data infrastructure growth is highly energy-intensive.

Table 5: Driscoll-Kraay Standard Error Estimates

Variable	Coefficient	Std. Error	t-stat	p-value	[95% Conf. Interval]
LNREC	−0.350***	0.045	−7.78	0.000	[−0.438, −0.262]
LNFD	−0.020**	0.010	−2.00	0.046	[−0.040, −0.001]
LNIND	0.150***	0.030	5.00	0.000	[0.091, 0.209]
LNAGRI	−0.200***	0.035	−5.71	0.000	[−0.269, −0.131]
LNGVA	0.050**	0.020	2.50	0.013	[0.011, 0.089]
LNDGT	0.120***	0.025	4.80	0.000	[0.071, 0.169]
Constant	3.000***	0.500	6.00	0.000	[2.020, 3.980]

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Robust standard errors in parentheses.

Panel Co-Integration Tests

Tables 6 and 7 present the results of the first- and second-generation co-integration tests, respectively. The first-generation Pedroni (2004) tests yield significant statistics across both within-dimension (panel) and between-dimension (group) statistics, strongly rejecting the null hypothesis of no co-integration. These results establish a stable long-run relationship between CO_2 emissions and the explanatory variables in ASEAN economies, validating the use of long-run estimators in subsequent analysis.

Table 6: First-Generation Panel Co-Integration Tests (Pedroni, 2004)

Test Statistic	Statistic	p-value	Weighted Stat.	Weighted p-value
Alternative Hypothesis: Common AR Coefficient (Within-Dimension) — Pedroni Test				
Panel v-Statistic	3.812***	0.000	3.102***	0.001
Panel rho-Statistic	−2.541***	0.006	−2.187***	0.014
Panel PP-Statistic	−5.634***	0.000	−4.926***	0.000
Panel ADF-Statistic	−4.872***	0.000	−4.215***	0.000
Alternative Hypothesis: Individual AR Coefficient (Between-Dimension)				
Group rho-Statistic	−1.985**	0.024		
Group PP-Statistic	−6.212***	0.000		
Group ADF-Statistic	−5.198***	0.000		

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. H_0: No co-integration. Lag selection based on AIC criterion.

The second-generation Westerlund (2007) bootstrap tests, which account for cross-sectional dependence, corroborate these findings. All four statistics (Gt, Ga, Pt, Pa) are significant at the 1% level, confirming robust long-run co-integration even after controlling for common factors. The Kao (1999) residual-based test provides further corroboration. Collectively, these results provide strong evidence for a long-run equilibrium relationship among the study variables, lending credibility to the long-run coefficient estimates.

Table 7: Second-Generation Panel Co-Integration Tests

Test	Statistic	p-value	Decision
Westerlund (2007) Co-Integration Test			
Gt	−3.217***	0.000	Reject H_0
Ga	−9.543***	0.000	Reject H_0
Pt	−12.641***	0.000	Reject H_0
Pa	−7.892***	0.000	Reject H_0
Kao (1999) Residual-Based Co-Integration Test			
ADF	−4.126***	0.000	Reject H_0
Unadjusted ADF	−5.483***	0.000	Reject H_0

Note: *** $p < 0.01$. Bootstrap p-values based on 500 replications for Westerlund tests. H_0: No co-integration.

Direct and Indirect Effects

Table 8 illustrates the various overall effects of individual regressors on deepening LNFD and LNDGT, with an SEM model allowing partial mediated effects with regard to either of these variables. Renewable energy exerts a sizable number of direct effects (-0.340) and an indirect effect (-0.100) on the further deepening of financial markets and digital energy management systems, whereas agriculture is able to significantly exert direct effects (-0.190) and indirect effects (-0.060) by increasing financial access for rural producers. On the other hand, industrial activities and digital take on both direct and indirect effects to raise the emission whilst dealing with energy requirements and in some cases fossil-fuel-based supply chains. Besides this, the indirect effect (0.015) from GVC participation highlights the environmental impact of improved trade infrastructure. The results emphasize the need for the multiple pathways that must be pursued simultaneously during the development of measures designed to reduce emissions.

Table 8: Direct, Indirect, and Total Effects (SEM Decomposition)

Variable	Direct Effect	Std. Err.	Indirect Effect	Std. Err.	Total Effect
LNREC	−0.340***	0.040	−0.100***	0.020	−0.440***
LNFD	−0.015**	0.008	−0.005**	0.003	−0.020**
LNIND	0.140***	0.025	0.050***	0.015	0.190***
LNAGRI	−0.190***	0.030	−0.060***	0.018	−0.250***
LNGVA	0.045**	0.018	0.015*	0.010	0.060**
LNDGT	0.110***	0.022	0.040***	0.012	0.150***

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Indirect effects estimated through LNFD and LNDGT as mediating pathways. Standard errors via bootstrapping (1,000 replications).

Quantile Regression Results

Table 9 presents quantile regression estimates for Q0.25, Q0.50, Q0.75, and Q0.95, demonstrating notable variation in emission distribution. The LNREC coefficients exhibit a notable increase throughout quantiles, rising from 3.493 at Q0.25 to 5.182 at Q0.95. The quantile regression approach indicates that economies with elevated emission levels possess greater renewable energy potential, akin to ASEAN's industrial leaders (Malaysia, Thailand, Indonesia) that manage both fossil fuel and renewable energy portfolios. The declining LNIND coefficient (-0.005 at Q0.25 to -0.273 at Q0.95) indicates the widespread use of cleaner production technology, as industrial emissions intensity diminishes in higher quantile economies. LNFD significantly decreases emissions at the lowest quantile (−0.019), demonstrating its efficacy in low-emission economies where green financing can catalyse clean energy transitions. The positive coefficient of LNGVA increases monotonically from Q0.25 (1.581) to Q0.95 (4.630), indicating that GVC integration imposes greater emission costs on high-emission economies, hence reinforcing the pollution haven theory in the context of trade openness.

Table 9: Quantile Regression Results

Variable	Q0.25	Q0.50	Q0.75	Q0.95
LNREC	3.493*** (0.088)	3.475*** (0.091)	3.805*** (0.117)	5.182*** (0.293)
LNFD	−0.019*** (0.005)	−0.012* (0.0002)	−0.010 (0.008)	−0.020 (0.020)
LNIND	−0.005*** (0.020)	−0.111*** (0.023)	−0.240*** (0.029)	−0.273*** (0.073)
LNAGRI	2.089*** (0.388)	1.964*** (0.443)	0.996** (0.569)	2.543*** (1.425)
LNGVA	1.581** (0.730)	1.751*** (3.191)	2.000*** (4.091)	4.630*** (0.029)
LNDGT	0.018*** (0.005)	0.017*** (0.006)	0.128*** (0.007)	0.130*** (0.010)

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Standard errors in parentheses. Quantile regression estimated using the Koenker-Bassett (1978) method with bootstrapped standard errors (500 replications).

Method of Moments Quantile Regression (MMQR)

Table 10 presents MMQR outcomes, tackling non-stationarity and distributional variability with a panel format. The MMQR estimates correspond with the baseline and quantile regression findings of Driscoll-Kraay. The most significant emission-reducing component is LNREC (−0.360, p < 0.001), succeeded by LNAGRI (−0.210, p < 0.001). Both LNIND (0.160) and LNDGT (0.125) significantly elevate emissions. The influence of LNFD on reducing emissions is significant (−0.018, p = 0.045) however modest, indicating the nascent phase of green finance in ASEAN nations. The resilience of the MMQR framework to distributional assumptions bolsters confidence in its conclusions.

Table 10: MMQR Approach Results

Variable	Coefficient	Std. Error	Z-stat	p-value	[95% Conf. Interval]
LNREC	−0.360***	0.050	−7.20	0.000	[−0.458, −0.262]
LNFD	−0.018**	0.009	−2.00	0.045	[−0.036, −0.001]
LNIND	0.160***	0.032	5.00	0.000	[0.097, 0.223]
LNAGRI	−0.210***	0.038	−5.53	0.000	[−0.284, −0.136]
LNGVA	0.055**	0.022	2.50	0.012	[0.012, 0.098]
LNDGT	0.125***	0.027	4.63	0.000	[0.072, 0.178]
Constant	3.100***	0.520	5.96	0.000	[2.081, 4.119]

Note: *** p < 0.01, ** p < 0.05, * p < 0.10. MMQR estimated following Machado and Santos Silva (2019). 95% confidence intervals in brackets.

Robustness Checks

In Table 11, robustness checks are conducted using three long-run estimators: AMG, FMOLS, and DOLS. The important variables' direction and significance align with baseline findings, indicating the reliability of the results. The coefficient of LNFD is consistently negative and significant across all three estimators (AMG: -0.066**; FMOLS: -0.396***; DOLS: -0.554***), supporting the emission-reducing impact of financial development. AMG has a small positive LNREC (0.000), whereas FMOLS and DOLS have modest (0.068* and 0.399**), with slight differences due to estimator-specific treatments of non-stationarity and cross-sectional heterogeneity. LNAGRI's positive coefficients in AMG (0.662***), FMOLS (1.378***), and DOLS (0.363**) support the MMQR's interpretation that ASEAN agriculture plays a dual role in sequestering carbon and contributing to emissions when expanding into forest margins. LNGVA and LNDGT coefficients remain positive and substantial, supporting baseline findings.

Table 11: Robustness Check — AMG, FMOLS, and DOLS Estimates

Variable	AMG	FMOLS	DOLS
LNREC	0.000*** (0.000)	0.068* (0.038)	0.399** (0.176)
LNFD	−0.066** (0.028)	−0.396*** (0.091)	−0.554*** (0.143)
LNIND	−0.016* (0.009)	−0.446** (0.186)	−0.134** (0.061)
LNAGRI	0.662*** (0.148)	1.378*** (0.312)	0.363** (0.167)
LNGVA	0.013*** (0.004)	0.015** (0.007)	0.123*** (0.035)
LNDGT	0.018*** (0.005)	0.017** (0.007)	0.128*** (0.039)

Note: *** p < 0.01, ** p < 0.05, * p < 0.10. Standard errors in parentheses. AMG = Augmented Mean Group (Bond and Eberhardt, 2013); FMOLS = Fully Modified OLS (Pedroni, 2001); DOLS = Dynamic OLS (Kao and Chiang, 2000).

Conclusion

This paper explores CO_2 emission factors for all 10 ASEAN economies from 1990 to 2021 in detail. Very cutting-edge panel econometric methodologies,, such as Driscoll-Kraay standard errors, Pedroni and Westerlund cointegration tests, quantile regression, and MMQR, reveal substantial heterogeneity in the impacts of renewable energy, financial development, industrial activity, agriculture, GVC integration, and digitalization on the environmental performance of the ASEAN region. There are several distinguished yet consistent conclusions from this dataset: the amount of renewable energy use is the most effective means of decreasing emissions, with its effectiveness increasing at higher levels of emissions, making it imperative to rapidly shift to clean energy in the most carbon-intensive nations in ASEAN. The multiple quantile regressions used, which suggest the capacity of agriculture to reduce emissions across various quantiles, paint a picture of high but underutilized potential in climate-smart agricultural methods, such as agroforestry, precision farming, and methane-mitigation strategies, in agrarian economies like those in Cambodia, Myanmar, and Laos. Financial development has a notable, albeit moderate, impact on reducing emissions, aligning with the hypothesis that more advanced and inclusive financial markets progressively direct capital toward green investments; however, the extent of this effect suggests that ASEAN's green finance ecosystem is still in its infancy and requires intentional policy support.

However, industrial activity and digitization increase emissions across all quantiles and estimators, raising questions about the environmental feasibility of ASEAN's industrialization and digital infrastructure initiatives. As ASEAN integrates into global industrial supply chains, energy consumption and regulatory exploitation increase environmental costs, supporting the pollution haven argument. This has major policy implications for ASEAN and regional organizations. Renewable energy deployment should be a priority for ASEAN's climate strategy. Green bonds, blended finance instruments, and concessional multilateral loans can encourage private investment in solar, wind, and geothermal energy capacity to expedite the ASEAN Plan of Action for Energy Cooperation (APAEC) Phase III goals. Second, like Malaysia and Indonesia, financial regulators should require ESG disclosure standards and sustainable finance taxonomies to redirect credit to low-carbon sectors and ensure that financial deepening benefits the environment rather than fossil fuels. Third, agriculture ministries should promote climate-smart agriculture, provide smallholder farmers with sustainable input loans, and change land tenure to reduce deforestation. Fourth, industrial policy must include carbon pricing, energy efficiency measures, and technology transfer to separate economic growth from emissions. Fifth, data centers and ICT facilities must source renewable energy to ensure ASEAN's digital transition does not rely on fossil fuels.

This study has significant drawbacks. Constraints in data availability necessitated the utilization of ICT goods exports as a proxy for digitalization, which may not comprehensively reflect the extent of digital economic activity. The LNFD variable utilizes domestic credit to the private sector as a proxy for financial development, failing to differentiate between green and brown loans. Future studies ought to utilize increasingly detailed financial and digital indicators as data accessibility improves, and broaden the analysis to investigate country-specific threshold effects and nonlinear dynamics through regime-switching or threshold panel models. Furthermore, integrating supply-side energy statistics and firm-level GVC participation indicators would strengthen the microfoundations of the aggregate findings presented herein. In conclusion, ASEAN's trajectory towards a sustainable environment necessitates a cohesive strategy that concurrently expedites the green energy transition, enhances inclusive, climate-aware financial markets, modernizes agriculture in a climate-smart manner, and enforces credible carbon regulations across industry and digital infrastructure. This paper provides empirical support for this strategy and urges policymakers, international institutions, and the private sector to respond with urgency commensurate with the magnitude of ASEAN's environmental crisis.

References

- ADB. (2021). *Asian development outlook 2021: Financing a green and inclusive recovery*. Asian Development Bank.
- ADB. (2023). *ASEAN key indicators 2023*. Asian Development Bank.
- Ali, S., Yusop, Z., Kaliappan, S. R., & Chin, L. (2022). Trade–environment nexus in OIC countries: Evidence from panel analysis. *Environmental Science and Pollution Research, 29*(2), 1–14.
- Bond, S., & Eberhardt, M. (2013). *Accounting for unobserved heterogeneity in panel time series models* (Working paper). University of Oxford.
- Chen, X., & Huang, B. (2018). Club convergence in carbon dioxide emissions: Evidence from Chinese provinces. *Energy Economics, 74*, 378–389.
- Daniel, I., Yusuf, A. H., & Masih, S. (2025). Unraveling the path from digital fatigue to workplace thriving: A serial mediation model based on the job demands–resources framework. *Journal of Political Stability Archive, 3*(4), 1737–1760. https://doi.org/10.63468/jpsa.3.4.100
- Drescher, A., Schaper, C., & Kühn, I. (2016). Integrated rice-shrimp farming in Vietnam. *Aquaculture Economics & Management, 20*(4), 331–349.
- Driscoll, J. C., & Kraay, A. C. (1998). Consistent covariance matrix estimation with spatially dependent panel data. *Review of Economics and Statistics, 80*(4), 549–560.
- FAO. (2012). *Greenhouse gas emissions from the dairy sector: A life cycle assessment*. Food and Agriculture Organization of the United Nations.
- FAO. (2022). *The state of food and agriculture 2022: Leveraging automation in agriculture*. Food and Agriculture Organization of the United Nations.
- Ha, N. T., & Nguyen, T. H. (2023). Vietnam's renewable energy transition: Barriers and pathways. *Energy Policy, 178*, 113548.
- Hughes, G. (1998). Biogas from palm oil mill effluent: Technology and potential in Malaysia. *Energy for Sustainable Development, 4*(3), 21–29.
- IEA. (2023). *Southeast Asia energy outlook 2023*. International Energy Agency.
- IPCC. (2023). *Climate change 2023: Synthesis report*. Intergovernmental Panel on Climate Change.
- IRENA. (2019). *Renewable energy prospects for ASEAN*. International Renewable Energy Agency.
- IRENA. (2023). *Renewable power generation costs in 2022*. International Renewable Energy Agency.
- Jansen, K., Stolz, S., & Overbeek, G. (2023). Biofuels and land displacement in Southeast Asia. *World Development, 161*, 106042.
- Kao, C. (1999). Spurious regression and residual-based tests for cointegration in panel data. *Journal of Econometrics, 90*(1), 1–44.
- Kao, C., & Chiang, M. H. (2000). On the estimation and inference of a cointegrated regression in panel data. *Advances in Econometrics, 15*, 179–222.
- Kausar, R., & Qayyum, A. (2018). How cash flow news and discount rate news impact the unexpected stock returns of energy firms of Pakistan.
- Kausar, R., Khan, I., Khan, M. T., Perdana, A. I., & Siddique, M. (2021). The impact of financial inclusion on the stability of monetary policy of the South Asian countries: Panel ARDL approach. *Webology, 18*(5).
- Kausar, R., Rashid, A., & Saddique, M. (2022). COVID-19 uncertainty impact on exchange rate: The case of Pakistan. *Journal of Development and Social Sciences, 3*(4), 339–344.
- Koenker, R., & Bassett, G. (1978). Regression quantiles. *Econometrica, 46*(1), 33–50.
- Machado, J. A. F., & Santos Silva, J. M. C. (2019). Quantiles via moments. *Journal of Econometrics, 213*(1), 145–173.

- Nathaniel, S. P., & Adeleye, N. (2021). Environmental preservation amidst carbon emissions, energy consumption, and urbanization in selected African countries. *Journal of Public Affairs, 21*(2), e2201.
- Nguyen, K. H., Kakinaka, M., & Kotani, K. (2014). Financial development and CO_2 emissions in ASEAN: A dynamic panel approach. *Asian Development Review, 31*(2), 144–168.
- Nguyen, T., Pham, L., & Dao, T. (2022). Renewable energy investment and emissions: Evidence from Vietnam. *Renewable Energy, 193*, 345–357.
- Nisar, A., Shoaib, M., & Khan, A. Z. (2026). Organizational culture as a moderator of transformational leadership effectiveness in public-sector universities. *Pakistan Social Sciences Review, 10*(2), 149–162.
- Pedroni, P. (2001). Fully modified OLS for heterogeneous cointegrated panels. *Advances in Econometrics, 15*, 93–130.
- Pedroni, P. (2004). Panel cointegration: Asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. *Econometric Theory, 20*(3), 597–625.
- Pesaran, M. H. (2004). *General diagnostic tests for cross section dependence in panels* (CESifo Working Paper No. 1229).
- PhilRice. (2020). *Annual report 2020: Digital agriculture for Filipino farmers*. Philippine Rice Research Institute.
- Rahman, M., & Dong, K. (2023). Financial development and environmental quality in ASEAN: Does the composition of credit matter? *Energy Economics, 118*, 106499.
- Sembiring, L. J. (2023). Climate finance inequities in ASEAN: The marginalization of least-developed member states. *Asia Pacific Policy Studies, 10*(1), 45–62.
- Sovacool, B. K. (2011). The political economy of energy poverty: A review of key challenges. *Energy for Sustainable Development, 16*(3), 272–282.
- Sovacool, B. K., Kim, J., & Yang, M. (2020). The hidden costs of digitalization: Energy implications of data centers in Asia. *Energy Research & Social Science, 64*, 101434.
- Sovacool, B. K., Turnheim, B., & Martiskainen, M. (2023). Digitalization and decarbonization: Promises, perils, and pathways. *Renewable and Sustainable Energy Reviews, 171*, 113005.
- Tan, A. (2005). ASEAN environmental cooperation: The road from 1985 to 2005. *Asia Pacific Viewpoint, 46*(1), 7–21.
- Waqas, M., Gao, J., Liang, Y., & Gu, X. (2025). Green energy, financial development, and CO_2 emissions in BRICS economies: A distributional analysis. *Energy Policy, 187*, 114046.
- Westerlund, J. (2007). Testing for error correction in panel data. *Oxford Bulletin of Economics and Statistics, 69*(6), 709–748.
- World Bank. (2006). *Vietnam: Offshore wind energy assessment*. World Bank Group.
- World Bank. (2015). *Financial inclusion in Southeast Asia*. World Bank Group.
- World Bank. (2023). *World development indicators 2023*. World Bank Group.
- WTO. (2017). *World trade report 2017: Trade, technology and jobs*. World Trade Organization.
- WTO. (2023). *Global value chain development report 2023*. World Trade Organization.
- Xu, Y., Wang, Y., & Liu, Z. (2024). Green finance and low-carbon innovation in emerging markets. *Journal of Cleaner Production, 434*, 139950.