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Innovation and Carbon Emissions: A Southeast Asian Perspective

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Abstract

In an era where sustainable development is paramount, understanding the relationship between innovation and environmental impact has become increasingly critical. As Southeast Asian (SEA) economies strive to transition toward more knowledge-based and technology-driven growth, it is crucial to assess whether innovation fosters sustainability or exacerbates environmental degradation. This study examines the impact of the innovation ecosystem on CO_2 emissions in selected SEA countries, utilizing various metrics from the Global Innovation Index (GII) grouped into five categories: institutions, human capital and research, infrastructure, market sophistication, and creative outputs. By employing Generalized Linear Models (GLMs) and conducting robustness checks with Robust Least Squares (RLS), the study reveals that all GII categories significantly impact CO_2 emissions. However, the findings indicate that this impact is positive, meaning that the innovation landscape in SEA continues to contribute to rising CO_2 emissions. The country-specific analysis also confirms that most of the GII categories are still not environmentally friendly. This evidence underscores the need for policymakers in SEA countries to prioritize the development of environmentally sustainable innovation frameworks that promote the adoption of inclusive green technologies and practices to mitigate the adverse effects of innovation on CO_2 emissions.

1. Introduction

The global push toward sustainable development, particularly in the face of climate change, has placed increasing emphasis on the role of innovation in shaping environmental outcomes [1–3]. In Southeast Asia (SEA), a region characterized by rapid industrialization and economic expansion, balancing economic progress with environmental sustainability remains a challenge [4–6]. The innovation ecosystem in SEA plays a pivotal role in driving economic growth through technological advancements, industrial modernization, and enhanced competitiveness [7–9]. As countries in the region continue to prioritize innovation as a key driver of economic development, understanding its broader implications—both positive and negative—is essential for crafting policies that foster sustainable growth.

However, despite the potential benefits of innovation, its impact on carbon dioxide (CO_2) emissions in SEA remains a pressing concern. While technological advancements and industrial infrastructure development have accelerated economic progress, they have also contributed to environmental degradation [10, 11]. A heavy reliance on fossil fuels, inefficient energy use, and weak regulatory frameworks have resulted in rising CO_2 emissions across the region [12–15]. Many industries remain carbon-intensive, and the adoption of green technologies has been slow due to economic and policy constraints [16–18]. Without strategic intervention, innovation-driven growth in SEA risks exacerbating environmental harm rather than mitigating it. Therefore, a critical examination of the region's innovation ecosystem and its environmental consequences is necessary to ensure that economic transformation aligns with long-term sustainability goals.

Despite the region's progress in fostering innovation, a fundamental issue persists: the innovation ecosystem in SEA has not been effectively aligned with sustainable environmental practices [19, 20]. The introduction of advanced technologies, expansion of industrial infrastructure, and increased market sophistication have inadvertently contributed to rising CO_2 emissions [21, 22]. While innovation is often associated with efficiency and environmental benefits, its impact on emissions is not always straightforward [23, 24]. In SEA, much of the innovation landscape is shaped by market-driven incentives rather than sustainability-oriented policies [25–27]. The challenge is further compounded by weak regulatory frameworks, limited adoption of green technologies, and a heavy reliance on manufacturing and extractive industries, which significantly contribute to carbon emissions [28–31]. Without proactive measures to integrate sustainability into innovation strategies, economic growth in SEA may continue to come at a high environmental cost.

A key issue is the absence of a structured approach to evaluating how different components of the innovation ecosystem contribute to environmental impact. While various studies have explored the effects of technological advancements on emissions, they often focus on broad measures such as R&D expenditures and patent activity, overlooking the systemic nature of innovation ecosystems [6, 32–38]. The Global Innovation Index (GII), developed by the World Intellectual Property Organization (WIPO), provides a comprehensive measure of innovation performance across countries [39]. However, its role in analyzing the environmental consequences of innovation remains underexplored, particularly in the SEA context. The need for an integrated assessment of how institutional quality, human capital development, infrastructure, market sophistication, and creative outputs influence CO_2 emissions is imperative for designing effective policy interventions. By examining these factors in greater detail, policymakers can develop targeted strategies to ensure that innovation not only drives economic progress but also fosters environmental sustainability.

Numerous studies have examined the impact of innovation on environmental sustainability, particularly in developed economies and major emerging markets [40–50]. Prior research has demonstrated that economies with strong innovation ecosystems tend to have lower emissions intensity due to increased efficiency, advanced technologies, and cleaner production processes. Studies also suggest that R&D investments and institutional quality play a significant role in shaping carbon emissions [51–55]. However, existing research presents several critical gaps. Most notably, the majority of studies on innovation and CO_2 emissions rely on macro-level indicators such as overall R&D expenditures, patent registrations, and technological diffusion, without considering the broader structural components of the innovation ecosystem. Furthermore, while research on innovation and environmental impact has been extensive in Western and East Asian economies, studies focusing on SEA remain limited. No prior study has systematically applied the GII metrics as an innovation ecosystem indicator to analyze CO_2 emissions in SEA. This leaves a significant gap in understanding the extent to which different components of innovation—such as institutions, human capital, infrastructure, market sophistication, and creative outputs—affect environmental outcomes in the region.

This study aims to bridge these gaps by conducting a comprehensive assessment of how different components of the innovation ecosystem, as measured by the GII, influence CO_2 emissions in selected SEA countries. By employing robust regression techniques, this research provides empirical evidence on the environmental impact of innovation in the region. Unlike previous studies that focus on generic innovation indicators, this research employs five key categories of the GII—institutions, human capital and research, infrastructure, market sophistication, and creative outputs—to provide a multidimensional perspective on the relationship between innovation and CO_2 emissions. Additionally, by focusing on SEA countries, the study offers region-specific evidence that can inform policymakers on how to balance innovation-driven economic growth with environmental sustainability. The findings will contribute to the development of environmentally sustainable innovation frameworks, emphasizing the need for inclusive green technologies, regulatory reforms, and targeted investments in clean energy and sustainable industries. By addressing these objectives, this study enhances the academic discourse on innovation and environmental sustainability while providing practical insights for policymakers and industry stakeholders in SEA.

2. Literature Review

2.1. Theoretical Review

This study is grounded in the endogenous growth theory, which posits that innovation, knowledge accumulation, and technological progress are key drivers of long-term economic growth [56–59]. Endogenous growth models emphasize the role of research and development (R&D), human capital, and institutional structures in fostering innovation-led economic expansion [60, 61]. However, these models have been extended in recent years to incorporate environmental considerations, highlighting the potential trade-offs between innovation and ecological sustainability [62]. While innovation-driven economic expansion theoretically leads to improved energy efficiency and sustainable development, the reality in SEA suggests that innovation continues to contribute to increasing carbon emissions [24].

The Environmental Kuznets Curve (EKC) hypothesis provides an additional theoretical foundation for this study, suggesting that as economies develop, environmental degradation initially worsens before improving as cleaner technologies and regulatory mechanisms take effect [63–66]. However, whether SEA countries are experiencing this transition remains an open question, particularly given their continued dependence on fossil fuels and energy-intensive industrial sectors [67]. The pace and effectiveness of this transition are influenced by factors such as policy implementation, technological adoption, and the availability of green financing, all of which vary significantly across the region [68].

Furthermore, the Porter Hypothesis suggests that well-designed environmental regulations can stimulate innovation, ultimately enhancing both economic performance and environmental quality [69–71]. This perspective argues that stricter environmental policies encourage firms to develop cleaner technologies and more efficient production processes, leading to a win-win scenario where both sustainability and competitiveness improve [72, 73]. However, in the context of SEA, weak regulatory enforcement and limited green investment may hinder this positive effect, raising concerns about whether innovation is truly being leveraged for environmental sustainability [74–76].

2.2. Empirical Review

Building on this theoretical foundation, a review of the empirical literature reveals a growing body of research examining the relationship between innovation and carbon emissions. Studies by Li et al. [77], Ganda [78], Töbelmann & Wendler [79], Khattak et al. [80], Obobisa et al. [81], Mongo et al. [82], Yu & Du [83], Chen & Lee [84], Mensah et al. [85], Su et al. [86], Li et al. [87], Rahman et al. [88], Adebayo et al. [89], Bergougui [90], and Khan et al. [91] provide diverse insights into this complex relationship. The findings indicate mixed results; while some research suggests that innovation leads to a reduction in carbon emissions [78, 81, 85, 91], others indicate that innovation may actually increase emissions [87–90]. Additionally, some studies report mixed findings [82], and variations in results often depend on the specific innovation indicators used [79, 83].

For instance, Li et al. [77] examined the impact of innovation on environmental quality across 30 Chinese regions, discovering an inverted U-shaped relationship between patent production and CO_2 emissions using the FEQR regression model for both less and more energy-intensive industries. Ganda [78] focused on OECD countries from 2000 to 2014, finding that increased levels of innovation correlate with decreased carbon emissions through the application of the System-GMM method. In contrast, Töbelmann & Wendler [79] studied the effects of green innovations on CO_2 emissions in EU-27 nations from 1992 to 2014, concluding that while general inventive activity does not reduce emissions, environmental innovation does. Khattak et al. [80] investigated the impact of innovation on carbon emissions in BRICS nations, utilizing the CCEMG estimator with data from 1980 to 2016, and found that, with the exception of Brazil, innovative initiatives have not succeeded in reducing carbon emissions in China, Russia, India, or South Africa. Similarly, Obobisa et al. [81] researched the effect of green technology innovation on environmental quality in 25 African nations from 2000 to 2018, finding that green technology significantly reduces CO_2 emissions.

Mongo et al. [82] analyzed the influence of environmental advances on sustainability in 15 European nations over a 23-year period using the ARDL approach, concluding that environmental innovations tend to reduce CO_2 emissions in the long run, although short-term effects may indicate a rebound effect. Yu & Du [83] explored how technological innovations affected carbon emissions in China from 1997 to 2015, revealing that autonomous innovation primarily contributed to the rise in CO_2 emissions, while the introduction of innovation also helped to lower emissions. Chen & Lee [84] examined the effect of technological innovation on environmental quality in 96 countries, using spatial panel data analysis from 1996 to 2018, and found that technological

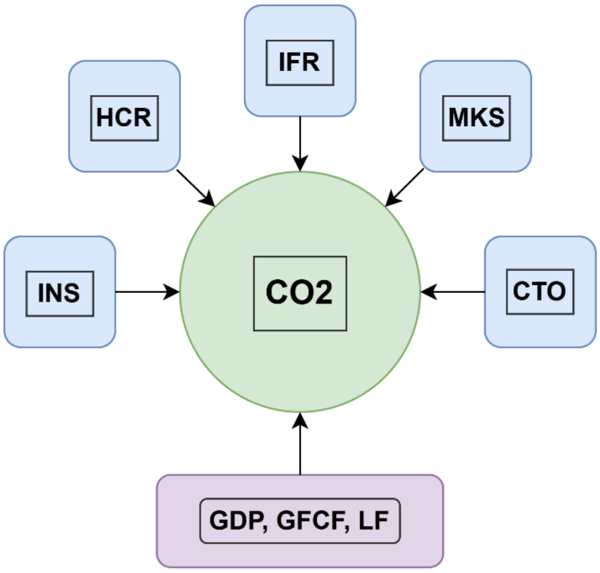

Figure 1. Conceptual framework of the study.

innovation does not have a discernible impact on reducing CO_2 emissions globally, although group-based research suggests that innovative technology in high-income, high-tech, and high-CO_2 generating nations may significantly lower emissions in neighboring countries.

Mensah et al. [85] conducted a study on the relationship between innovation and carbon emissions in 28 OECD member countries from 1990 to 2014, employing the STIRPAT model, and concluded that innovation plays a crucial role in reducing CO_2 emissions in most OECD nations. Conversely, Su et al. [86] found that two of the three technological innovation tools examined increased carbon emissions in BRICS nations. Li et al. [87] investigated the impact of technological innovation on environmental sustainability in MINT nations from 2000 to 2020, using FMOLS and DOLS methodologies, and revealed that technological innovation exacerbates environmental deterioration in these countries. Rahman et al. [88] analyzed the effects of technological innovations on carbon emissions in 22 developed nations from 1990 to 2018, employing the NARDL approach, and found that negative shocks from technological innovation lead to increased carbon emissions.

In Portugal, Adebayo et al. [89] evaluated the relationship between environmental quality and technological innovation using a dataset from 1980 to 2019. Their analysis, which included frequency domain causality analysis and wavelet coherence methods, revealed that technological innovation contributes to rising carbon emissions. Bergougui [90] examined the impact of technological innovations on environmental sustainability in Algeria, utilizing the NARDL approach with data from 1980 to 2021, and found that technological innovation leads to environmental deterioration. Lastly, Khan et al. [91] studied the effect of technological advancement on environmental sustainability in G-7 nations, using data from 1990 to 2020 and the CS-ARDL approach, concluding that technological innovation decreases carbon emissions in both the short and long term.

The literature reveals a complex and nuanced relationship between innovation and carbon emissions, with findings varying significantly across regions and contexts. While some studies suggest that innovation reduces carbon emissions, others highlight its potential to increase emissions, particularly in economies reliant on fossil fuels. This underscores the need to understand the specific mechanisms through which innovation influences environmental sustainability. As SEA pursues economic growth amid pressing environmental challenges, further research is crucial to exploring how innovation can be effectively leveraged for sustainable development. This study contributes to this discourse by examining the intricate dynamics between inclusive innovation—measured through the Global Innovation Index (GII)—and carbon emissions in SEA, ultimately informing policy and practice for a more sustainable future.

2.3. Conceptual Framework

As illustrated in Figure 1, the conceptual framework of the study emphasizes the interrelationships between various independent metrics category of GII and their impact on CO_2 emissions. The framework is grounded in the endogenous growth model, adjusted to incorporate the EKC and Porter hypotheses, which posit that sustainable economic growth is primarily driven by internal factors, supported by well-designed environmental regulations, rather than external influences. This highlights the crucial role of investment, human capital, innovation, and policy frameworks in fostering long-term, eco-friendly economic development [62, 92, 93]. In this context, the GII metrics categorized—namely, Institution (INS), Human Capital and Research (HCR), Infrastructure (IFR), Market Sophistication (MKS), and Creative Outputs (CTO)—are pivotal in shaping the economic landscape and, consequently, CO_2 emissions.

Each of these metrics plays a crucial role in fostering innovation and economic activity, which can lead to increased CO_2 emissions. For instance, a robust institutional framework (INS) can enhance regulatory environments, encouraging sustainable practices that mitigate emissions [94, 95]. Similarly, investments in human capital and research (HCR) can lead to technological advancements that improve energy efficiency and reduce carbon footprints [96, 97].

Table 1. Variable synopsis.

Variable	Symbol	Description	Units (Sources)	Variable's detail
Dependent	CO2	CO_2 emissions	Tonnes (OWID) [98]	Represents the release of carbon dioxide gas into the atmosphere, primarily as a byproduct of human activities such as burning fossil fuels, deforestation, and industrial processes.
Control Independent	GDP	Gross domestic product	Constant LCU (WDI) [99]	Represents the total gross value added by all producers residing within the economy.
	GFCF	Gross fixed capital formation	Constant LCU (WDI) [99]	Represents the total gross value added from investments in land improvements, the acquisition of plant, machinery, and equipment, as well as the construction of public infrastructure.
	LF	Labor force	Person (WDI) [99]	Represents individuals aged 15 and older who provide labor for the production of goods and services.
Main Independent	INS	Institution	Scale 1-100 (WIPO) [39]	Represents metrics such as the political, regulatory, and business environment.
	HCR	Human capital and research		Represents metrics such as education, tertiary education, and research and development (R&D).
	IFR	Infrastructure		Represents metrics such as information and communication technologies, general infrastructure, and ecological sustainability.
	MKS	Market sophistication		Represents metrics such as credit, investment, trade, competition, and market scale.
	CTO	Creative outputs		Represents metrics such as intangible assets, creative goods and services, and online creativity.

Infrastructure (IFR) is essential for supporting economic activities, and its development can either exacerbate or alleviate environmental impacts depending on the technologies employed [100, 101]. Market sophistication (MKS) and creative outputs (CTO) further contribute to this dynamic by promoting competitive practices and innovative solutions that can either increase or decrease emissions based on their nature [102, 103].

The control independent variables—GDP, GFCF, and LF—are also integrated into this framework, reflecting the broader economic context in which these metrics operate. As economic growth accelerates, it often correlates with higher CO_2 emissions due to increased production and consumption activities [50, 104, 105]. However, the framework suggests that by leveraging the GII metrics category effectively, it is possible to achieve a balance where economic growth does not come at the expense of environmental sustainability. This interplay highlights the importance of innovation and strategic policy-making in addressing the challenges of climate change while fostering economic development.

3. Methodology

3.1. Data and Variable

The study focuses on Southeast Asian (SEA) countries. However, due to incomplete data from the Global Innovation Index (GII) for several SEA countries, it excludes Brunei Darussalam, Laos, Myanmar, and Timor-Leste. Thus, the selected SEA countries for this study are Cambodia, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam. Study's employed data covering the years 2011 to 2023, justified by the fact that the earliest available data for the Global Innovation Index (GII) dates back to 2011, while the latest data for the other variables extends to 2023. Furthermore, due to the relatively short timeframe, the study transformed annual data into semi-annual intervals to improve the robustness and reliability of the regression estimates.

There are seven metrics categories in the GII [39], but the study excludes the business sophistication and knowledge and technology outputs categories as they do not pass the cross-sectional dependence test, which is an important preliminary test for panel data. Thus, the five GII categories used in this study are institution, human capital and research, infrastructure, market sophistication, and creative outputs. The Institutions category assesses the political, regulatory, and business environment, considering factors like political stability, government effectiveness, regulatory quality, and the ease of doing business. Human capital and research focuses on the quality of education from primary to higher levels, research and development (R&D) investments, the number of researchers, and university-industry collaboration in innovation. Infrastructure examines the development of information and communication technologies (ICTs), electricity supply, ecological sustainability, and overall infrastructure quality that supports innovation. Market sophistication evaluates financial systems, including access to credit, venture capital availability, and trade conditions that facilitate business growth and competitiveness. Finally, creative outputs measure innovation in the form of intangible assets such as trademarks and industrial designs, the production of creative goods and services, and digital creativity indicators like domain registrations and mobile app development.

The employed variables of the study consist of CO_2 emissions (CO2) as the dependent variable, five GII categories as the main independent variables, and gross domestic product (GDP), gross fixed capital formation (GFCF), and labor force (LF) as control independent variables. CO2 data was sourced from Our World in Data [98], GII data was obtained from the World Intellectual Property Organization (WIPO) [39], and GDP, GFCF, and LF data were sourced from the World Bank's World Development Indicators (WDI) [99]. Table 1 presents details about the variables used in this study.

3.2. Model Specification

This study investigates the impact of five key GII metric categories—INS, HCR, IFR, MKS, and CTO—on CO_2 emissions, analyzing each separately in different models while incorporating GDP, GFCF, and LF as control variables. By exploring the relationships among these variables, the study seeks to uncover the underlying mechanisms influencing CO_2 emissions. The mathematical representation of this relationship is provided in Equation 1.

$$CO2 = f(GDP, GFCF, LF, GII) \tag{1}$$

Where $CO2$ represents CO_2 emissions, GDP represents gross domestic product, $GFCF$ represents gross fixed capital formation, LF represents labor force, and GII stands for global innovation index metrics category. Specifically, the relationship between variables in the practical econometric model, examined using the decomposition approach, is depicted in Equations 2–6.

Furthermore, since each variable has a different unit of measurement, all variables were transformed into their natural logarithmic (ln) form to ensure that the regression coefficients could be interpreted as percentage changes. The final econometric model used in this study is presented in Equations 7–11.

In the equations, i represents the country, t represents the study period, β_0 denotes the intercept, $\beta_1 - \beta_4$ represent the coefficients, and ε is the error term.

$$CO2_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GFCF_{it} + \beta_3 lnLF_{it} + \beta_4 \begin{bmatrix} INS_{it} \\ HCR_{it} \\ IFR_{it} \\ MKS_{it} \\ CTO_{it} \end{bmatrix} + \varepsilon_{it} \tag{2-6}$$

$$lnCO2_{it} = \beta_0 + \beta_1 lnGDP_{it} + \beta_2 lnGFCF_{it} + \beta_3 lnLF_{it} + \beta_4 \begin{bmatrix} lnINS_{it} \\ lnHCR_{it} \\ lnIFR_{it} \\ lnMKS_{it} \\ lnCTO_{it} \end{bmatrix} + \varepsilon_{it} \tag{7-11}$$

3.3. Methods

3.3.1. Generalized Linear Models (GLMs)

The GLMs is a versatile statistical framework that extends traditional linear regression to accommodate a variety of response variable types, including continuous data as this study utilized. One of the significant advantages of using GLMs is their ability to handle various types of data while maintaining interpretability. This is particularly beneficial when dealing with non-normal distributions, as it allows for more accurate modeling of the underlying processes [106]. Additionally, GLMs can be adjusted for panel data, which consists of observations over time for the same subjects. By incorporating generalized estimating equations (GEEs), the method can account for the correlation between observations within the same subject, leading to more robust estimates and valid inferences [107].

GLMs also mitigate specific classical assumptions that traditional linear regression models impose, such as homoscedasticity and normality of residuals. In a standard linear regression framework, violations of these assumptions can lead to inefficient estimates and invalid hypothesis tests. However, GLMs allow for the modeling of heteroscedasticity by using appropriate link functions and distributions, thus providing a more accurate representation of the data [108]. Furthermore, by accommodating non-normal response distributions, GLMs reduce the risk of biased estimates and enhance the reliability of statistical inferences, making them a powerful tool for analyzing complex datasets [109].

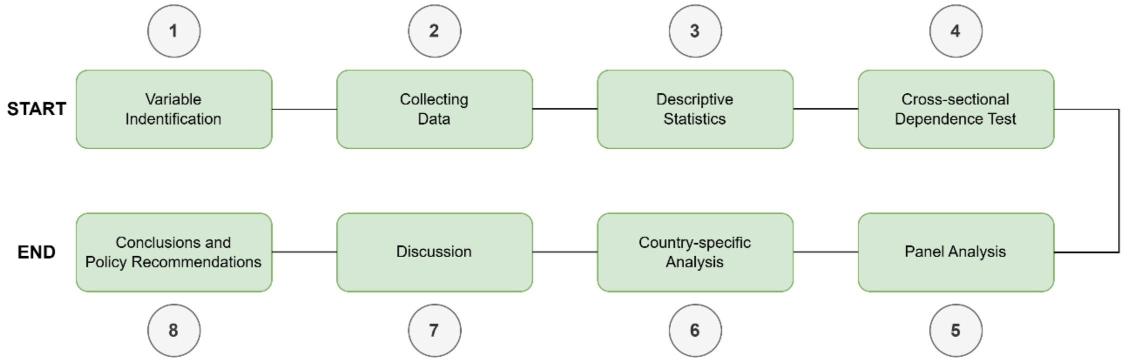

Figure 2. Flow analysis of the study.

Table 2. Descriptive statistics of the panel dataset.

Variable	Mean	Median	Max.	Min.	Std. Dev.	Skewness	Kurtosis	Jarque-Bera
lnCO2	18.680	19.188	20.413	15.478	1.2578	-0.9436	3.0352	27.018
lnGDP	26.270	26.566	27.796	23.339	1.1183	-1.4782	4.3254	79.605
lnGFCF	24.916	25.163	26.646	21.587	1.2026	-1.3513	4.3235	68.669
lnLF	17.014	17.509	18.767	14.942	1.1600	-0.3436	2.0157	10.928
lnINS	4.0502	3.9964	4.5890	3.2347	0.2706	0.2496	3.1668	2.1009
lnHCR	3.3853	3.3878	4.3095	2.4069	0.4625	0.0717	2.5516	1.6804
lnIFR	3.6619	3.7013	4.2413	3.0204	0.2972	-0.0991	2.4656	2.4639
lnMKS	3.9215	3.8918	4.3656	3.4243	0.2237	0.1187	2.5329	2.0813
lnCTO	3.3852	3.4719	3.8286	1.9879	0.3194	-1.3869	6.1441	133.31

3.3.2. Robust Least Squares (RLS)

RLS is a statistical technique designed to provide reliable estimates in the presence of outliers or violations of the classical assumptions of ordinary least squares (OLS) regression. Traditional OLS regression is sensitive to outliers, which can disproportionately influence the estimated coefficients and lead to misleading conclusions. RLS addresses this issue by employing methods that reduce the impact of outliers on the estimation process, allowing for more accurate modeling of the underlying relationships in the data [18, 110].

One of the primary advantages of RLS is its ability to produce stable estimates even when the data contains outliers or is not normally distributed. By using techniques such as M-estimators, RLS minimizes a different loss function compared to traditional OLS, which focuses on minimizing the sum of squared residuals. This shift in focus allows the method to down-weight the influence of outliers, leading to more reliable parameter estimates and improved model performance [111, 112]. Thus, RLS is suitable for robustness checks in GLMs, providing a complementary approach to validate the findings of GLMs analyses. This is particularly important in ensuring that the results are not unduly affected by outliers or model assumptions.

3.4. Flow Analysis

Figure 2 illustrates the flow analysis of the study, outlining the systematic approach taken to investigate the research questions. The process begins with Variable Identification (1), where key variables relevant to the study are defined and selected. This is followed by Collecting Data (2), which involves gathering the necessary information for analysis. Once the data is collected, Descriptive Statistics (3) are performed to summarize and understand the basic features of the dataset. The next step involves conducting a Cross-sectional Dependence Test (4) to assess the relationships between variables across different observations. Following these preliminary analyses, the study progresses to Panel Analysis (5) and Country-specific Analysis (6) using GLMs and RLS methods, leading to a comprehensive Discussion (7) of the findings. Finally, the study concludes with Conclusions and Policy Recommendations (8), synthesizing the results and suggesting actionable insights for policymakers based on the analysis. This structured flow ensures a thorough examination of the research objectives while maintaining clarity and coherence throughout the study.

4. Results

4.1. Descriptive Statistics

Table 2 provides descriptive statistics for a panel dataset, focusing on the natural logarithm of various employed variables. The variable lnCO2 has a mean of 18.680 and a median of 19.188, indicating a slight negative skewness of -0.9436, suggesting a concentration of higher CO_2 emissions. lnGDP shows a mean of 26.270 and a

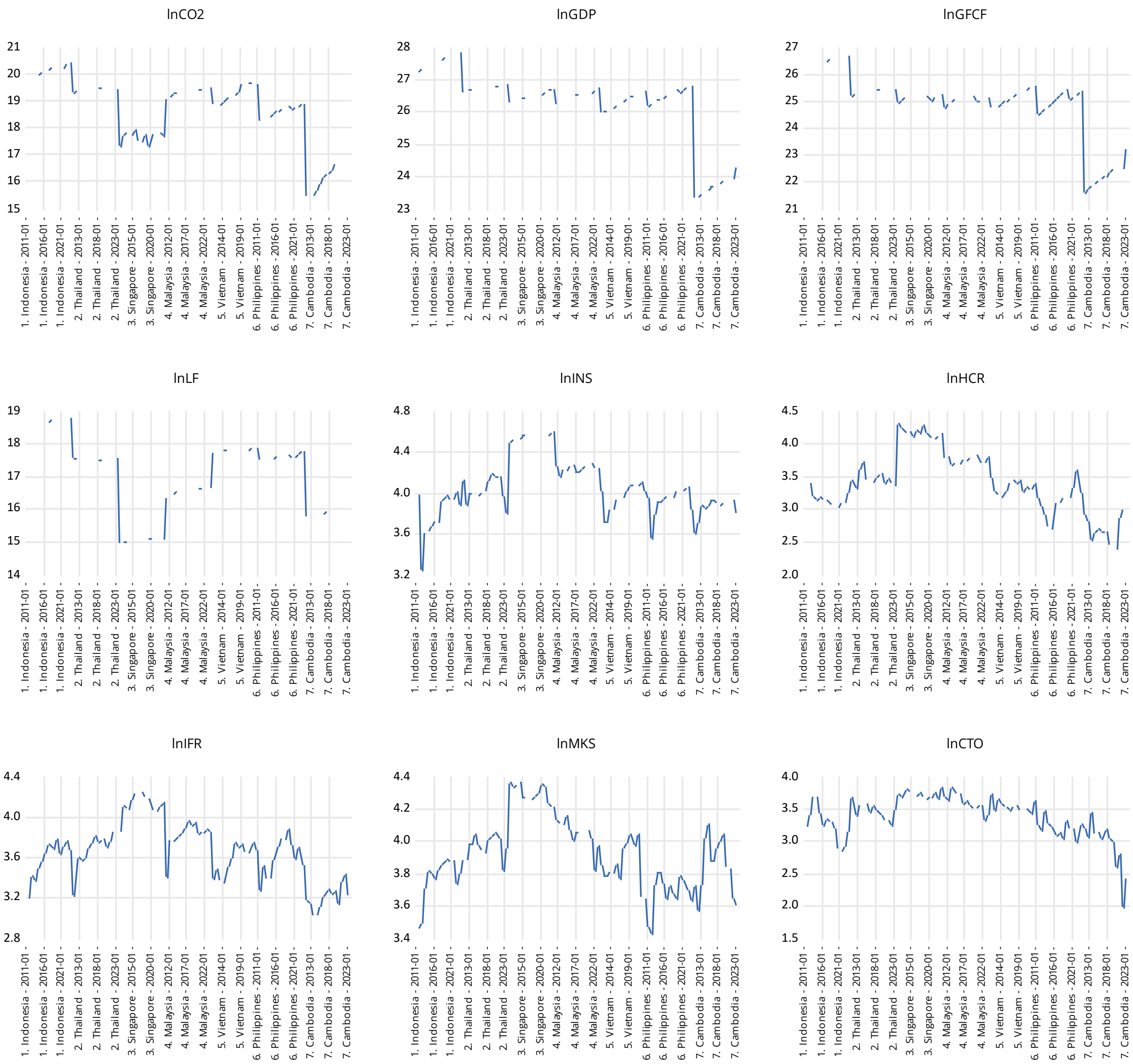

Figure 3. Graphical representation of the country-specific dataset.

median of 26.566, with a leftward skewness of -1.4782, reflecting a few countries with significantly higher GDP levels. Similarly, lnGFCF has a mean of 24.916 and a skewness of -1.3513, while lnLF presents a mean of 17.014 and a slight leftward skew of -0.3436, indicating moderate variability in labor force data.

For the main independent variables, lnINS has a mean of 4.0502 and a median of 3.9964, with a slight rightward skewness of 0.2496, suggesting a distribution leaning toward higher values. lnHCR shows a mean of 3.3853 and a median of 3.3878, with a skewness of 0.4065, indicating a slight rightward tail. The variable lnIFR has a mean of 3.6619 and a nearly symmetrical distribution (skewness of -0.0991), while lnMKS presents a mean of 3.9215 with a slight rightward skew of 0.1187. Finally, lnCTO has a mean of 3.3852 and a leftward skew of -1.3869, highlighting a more concentrated distribution of creative outputs.

Meanwhile, Figure 3 illustrates the temporal trends of various country-specific datasets. The lnCO2 emissions exhibit fluctuations, peaking around 21 before trending downward, possibly indicating improvements in emission control or shifts in industrial activity. The lnGDP graph shows a steady increase, reaching a plateau around 27, suggesting stable economic growth over the observed period. Similarly, lnGFCF exhibits a gradual upward trend, reflecting consistent investment in fixed capital, which is essential for economic development. In contrast, the lnLF variable reveals a more volatile pattern, fluctuating between 14 and 19, indicating variability in labor force participation over time.

The main independent variables present a mixed picture. The lnINS variable demonstrates a relatively stable trend, oscillating around 4.0, suggesting consistent institutional performance. The lnHCR graph shows slight fluctuations, with values hovering between 3.0 and 4.5, indicating

Table 3. Results of cross-sectional dependence test.

Test	Stat. (Prob.)				
	INS Model	*HCR Model*	*IFR Model*	*MKS Model*	*CTO Model*
Breusch-Pagan LM	128.82* (0.0000)	87.487* (0.0000)	154.71* (0.0000)	73.083* (0.0000)	124.47* (0.0000)
Pesaran scaled LM	16.637* (0.0000)	10.259* (0.0000)	20.632* (0.0000)	8.0367* (0.0000)	15.965* (0.0000)
Pesaran CD	2.5159** (0.0119)	2.0129** (0.0441)	2.9257* (0.0034)	3.4649* (0.0005)	7.6243* (0.0000)

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

variability in human capital and research metrics. The lnIFR displays a steady increase, peaking at around 4.0, reflecting improvements in infrastructure. In contrast, both lnMKS and lnCTO exhibit downward trends, with lnMKS fluctuating around 4.0 and lnCTO declining to approximately 2.0, suggesting challenges in market sophistication and creative outputs over the observed period.

4.2. Cross-Sectional Dependence Test

Table 3 presents the results of cross-sectional dependence tests for various models, including INS, HCR, IFR, MKS, and CTO. The tests conducted include the Breusch-Pagan LM, Pesaran scaled LM, and Pesaran CD, with corresponding statistics and p-values indicating the significance of the results. Together, these tests provide a comprehensive assessment of cross-sectional dependence, effectively accounting for heteroscedasticity and remaining robust against both small and large sample sizes, ensuring reliable results [113, 114].

For the Breusch-Pagan LM test, the INS Model shows a statistic of 128.82 with a p-value of (0.0000), indicating strong evidence of cross-sectional dependence at the 1% significance level. Similarly, the HCR Model has a statistic of 87.487 and a p-value of (0.0000), also confirming significant dependence. The IFR Model exhibits the highest statistic at 154.71, with a p-value of (0.0000), further reinforcing the presence of cross-sectional dependence. The MKS Model and CTO Model also show significant results, with statistics of 73.083 and 124.47, respectively, both with p-values of (0.0000).

In the Pesaran scaled LM test, the INS Model again shows a strong statistic of 16.637 with a p-value of (0.0000), indicating significant dependence. The HCR Model has a statistic of 10.259, also significant at the 1% level. The IFR Model shows a statistic of 20.632, while the MKS Model and CTO Model have statistics of 8.0367 and 15.965, respectively, all with p-values indicating significance.

Lastly, the Pesaran CD test results show the INS Model with a statistic of 2.5159 ($p = 0.0119$), indicating significance at the 5% level. The HCR Model has a statistic of 2.0129 ($p = 0.0441$), also significant at the 5% level. The IFR Model shows a statistic of 2.9257 ($p = 0.0034$), while the MKS Model and CTO Model have statistics of 3.4649 and 7.6243, respectively, both significant at the 1% level. Overall, the results across all tests consistently indicate significant cross-sectional dependence among the models, suggesting that the observations are not independent and may influence one another.

4.3. Panel Analysis

4.3.1. GLMs Estimation

The first estimation results of the study in Table 4 present the GLMs findings, highlighting the coefficients and significance levels of the variables lnINS, lnHCR, lnIFR, lnMKS, and lnCTO in relation to lnCO2 in their respective models. In the INS Model, lnINS has a coefficient of 1.1749 with a p-value of 0.0000, indicating a strong and significant positive relationship with lnCO2 emissions. This suggests that improvements or increases in institutional metrics are associated with higher CO_2 emissions. In the HCR Model, lnHCR shows a coefficient of 0.9466 ($p=0.0000$), also indicating a significant positive relationship with lnCO2, implying that higher human capital and research metrics contribute to increased emissions.

The IFR Model presents lnIFR with a coefficient of 0.5368 ($p=0.0000$), reinforcing the significant positive impact of infrastructure on CO2 emissions. In the MKS Model, lnMKS has a coefficient of 0.6407 ($p=0.0000$), indicating that market sophistication is positively associated with lnCO2 emissions, suggesting that more sophisticated markets may lead to higher emissions. Lastly, in the CTO Model, lnCTO has a coefficient of 0.3565 ($p=0.0022$), which is also significant, indicating that creative outputs are positively related to CO_2 emissions. Overall, the results consistently show that lnINS, lnHCR, lnIFR, lnMKS, and lnCTO have significant positive relationships with lnCO2, suggesting that various factors related to institutions, human capital, infrastructure, market sophistication, and creative outputs contribute to increased CO_2 emissions in SEA.

In addition to the significant relationships observed for GII metric categories, the lnLF variable also demonstrates a positive relationship with lnCO2 emissions. With a coefficient ranging from 0.4778 to 0.7799 ($p=0.0000$) across all models, this indicates that an increase in the

Table 4. Results of panel GLMs estimation.

Dependent: lnCO2					
Variable	**Coeff. (Prob.)**				
	INS Model	*HCR Model*	*IFR Model*	*MKS Model*	*CTO Model*
C	-11.672* (0.0000)	-6.8950* (0.0000)	-7.5446* (0.0000)	-12.773* (0.0000)	-7.5137* (0.0000)
lnGDP	0.2568 (0.2214)	0.1803 (0.3721)	0.3064 (0.1683)	0.5601* (0.0082)	0.3048 (0.1643)
lnGFCF	0.2697 (0.1781)	0.1752 (0.3644)	0.2865 (0.1806)	0.0588 (0.7769)	0.3552*** (0.0881)
lnLF	0.7128* (0.0000)	0.7799* (0.0000)	0.5368* (0.0000)	0.6407* (0.0000)	0.4778* (0.0000)
lnINS	1.1749* (0.0000)				
lnHCR		0.9466* (0.0000)			
lnIFR			0.5202** (0.0258)		
lnMKS				1.1167* (0.0000)	
lnCTO					0.3565* (0.0022)

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

Table 5. Results of panel RLS estimation.

Dependent: lnCO2					
Variable	**Coeff. (Prob.)**				
	INS Model	*HCR Model*	*IFR Model*	*MKS Model*	*CTO Model*
C	-11.271* (0.0000)	-6.9357* (0.0000)	-7.1260* (0.0000)	-11.956* (0.0000)	-7.0974* (0.0000)
lnGDP	0.1675 (0.4527)	0.1781 (0.4104)	0.1208 (0.6047)	0.3040 (0.1671)	0.1765 (0.4467)
lnGFCF	0.3482 (0.1017)	0.1639 (0.4277)	0.4089*** (0.0685)	0.2815 (0.1914)	0.4675** (0.0339)
lnLF	0.7155* (0.0000)	0.7958* (0.0000)	0.5819* (0.0000)	0.6537* (0.0000)	0.4832* (0.0000)
lnINS	1.1561* (0.0000)				
lnHCR		0.9742* (0.0000)			
lnIFR			0.6877* (0.0050)		
lnMKS				1.1412* (0.0000)	
lnCTO					0.3699* (0.0027)

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

labor force is associated with higher CO_2 emissions. This trend exacerbates environmental concerns, as a growing labor force often correlates with increased industrial activity and energy consumption, leading to higher emissions. The combined effects of these variables suggest that not only the innovation ecosystem but also labor dynamics play a crucial role in influencing CO_2 emissions in SEA, highlighting the multifaceted nature of environmental challenges.

4.3.2. Robustness Check with RLS Estimation

Table 5 presents the results of the RLS estimation, conducted to assess the robustness and consistency of the previous GLM results for the variables lnINS, lnHCR, lnIFR, lnMKS, and lnCTO in relation to lnCO2. The findings indicate that all models yield similar results to those of the GLMs, with all GII metrics categories showing positive coefficients ranging from 0.3699 to 1.1561, all accompanied by significant p-values. These RLS results consistently confirm that lnINS, lnHCR, lnIFR, lnMKS, and lnCTO have a significant positive impact on lnCO2, further highlighting the crucial roles of institutional factors, human capital, infrastructure, market sophistication, and creative outputs in driving the rise in CO_2 emissions. Additionally, the lnLF variable in the RLS results reveals a positive relationship with lnCO2 emissions, consistent with the findings from the GLMs. This reinforces the notion that labor activity within a non-environmentally friendly innovation ecosystem contributes to the complexity of environmental challenges.

4.4. Country-Specific Analysis

4.4.1. GLMs Estimation

Delving into country-specific analysis, GLM findings in Table 6 show mixed results. However, in general, most of the GII metric categories have a positive relationships with lnCO2. lnINS is found to have a significant impact on lnCO2 in Singapore and the Philippines, with both showing a positive coefficient. In other countries, despite not being significant, it also shows a positive coefficient. This suggests that improvements in institutional metrics in SEA are associated with increased CO_2 emissions. In contrast, lnHCR mostly shows a negative coefficient, with a significant impact on lnCO2 observed in Indonesia, Singapore, Vietnam, and Cambodia. This indicates that higher levels of human capital and research in SEA may contribute to reducing CO_2 emissions, potentially due to advancements in green technologies or more efficient resource utilization.

lnIFR demonstrates a significant effect on lnCO2 in Thailand and Vietnam, with a positive coefficient in Thailand and a negative coefficient in Vietnam. These

Table 6. Results of country-specific GLMs estimation.

Dependent: lnCO2								
Model	**Variable**	**Coeff. (Prob.)**						
		Indonesia	*Thailand*	*Singapore*	*Malaysia*	*Vietnam*	*Philippines*	*Cambodia*
INS Model	C	-30.5* (0.00)	59.3* (0.00)	28.4*** (0.09)	0.26 (0.86)	5.57 (0.78)	-5.62* (0.00)	-79.1* (0.00)
	lnGDP	1.26 (0.07)	0.29 (0.49)	-0.23 (0.76)	-0.45 (0.10)	-0.38 (0.70)	1.05* (0.00)	-1.69 (0.15)
	lnGFCF	-1.46** (0.01)	-0.12 (0.81)	-0.36 (0.63)	0.02 (0.82)	1.47*** (0.08)	0.09*** (0.05)	-0.02 (0.96)
	lnLF	2.91* (0.00)	-2.54* (0.00)	-3.04 (0.20)	1.86* (0.00)	-0.83 (0.53)	-0.35* (0.01)	8.53* (0.00)
	lnINS	0.01 (0.88)	-0.04 (0.42)	11.0** (0.04)	-0.06 (0.72)	0.40 (0.13)	0.06*** (0.09)	0.11 (0.62)
HCR Model	C	-24.9* (0.00)	61.4* (0.00)	34.3** (0.03)	1.04 (0.49)	16.3 (0.38)	-4.92* (0.00)	-82.5* (0.00)
	lnGDP	0.67 (0.22)	0.24 (0.56)	0.01 (0.98)	-0.28 (0.31)	-2.07** (0.03)	1.07* (0.00)	-0.99 (0.30)
	lnGFCF	-0.28 (0.62)	-0.08 (0.87)	0.10 (0.88)	-0.01 (0.93)	3.03* (0.00)	0.10*** (0.05)	-0.34 (0.47)
	lnLF	1.75** (0.04)	-2.65* (0.00)	-0.87 (0.63)	1.60* (0.00)	-0.97 (0.45)	-0.42* (0.00)	8.21* (0.00)
	lnHCR	0.38* (0.00)	-0.04 (0.56)	-1.54* (0.00)	-0.19 (0.14)	-0.34*** (0.08)	0.02 (0.37)	-0.21* (0.00)
IFR Model	C	-35.5* (0.00)	46.7* (0.00)	61.4*** (0.08)	-0.42 (0.90)	4.72 (0.80)	-4.96* (0.00)	-75.1* (0.00)
	lnGDP	1.55** (0.02)	0.56 (0.11)	2.18 (0.12)	-0.45 (0.12)	-2.29** (0.01)	1.11* (0.00)	-2.18 (0.11)
	lnGFCF	-2.29 (0.01)	-0.89*** (0.06)	-1.60 (0.21)	0.04 (0.78)	3.32* (0.00)	0.11 (0.11)	0.24 (0.75)
	lnLF	3.89* (0.00)	-1.17 (0.16)	-4.52 (0.18)	1.85* (0.00)	-0.40 (0.76)	-0.48** (0.01)	8.63* (0.00)
	lnIFR	0.23 (0.27)	0.23* (0.00)	1.62 (0.11)	-0.02 (0.86)	-0.47** (0.03)	-0.02 (0.66)	0.12 (0.70)
MKS Model	C	-20.4* (0.00)	57.7* (0.00)	-4.99 (0.85)	0.34 (0.85)	7.32 (0.70)	-5.51* (0.00)	-79.2* (0.00)
	lnGDP	0.46 (0.18)	0.09 (0.83)	0.27 (0.73)	-0.46 (0.12)	0.45 (0.71)	1.07* (0.00)	-1.81 (0.10)
	lnGFCF	0.26 (0.45)	0.12 (0.81)	0.40 (0.67)	0.03 (0.73)	0.96 (0.32)	0.09*** (0.06)	0.04 (0.94)
	lnLF	1.23** (0.02)	-2.51* (0.00)	0.08 (0.96)	1.84* (0.00)	-1.41 (0.27)	-0.39** (0.01)	8.63* (0.00)
	lnMKS	-0.53* (0.00)	0.05 (0.61)	0.94 (0.48)	-0.02 (0.84)	0.29*** (0.06)	0.03 (0.42)	0.09 (0.34)
CTO Model	C	-28.1** (0.01)	57.6* (0.00)	10.4 (0.50)	-0.53 (0.79)	17.7 (0.36)	-4.93* (0.00)	-85.7* (0.00)
	lnGDP	1.09 (0.12)	0.16 (0.71)	0.43 (0.58)	-0.29 (0.51)	-1.11 (0.19)	1.10* (0.00)	-1.69 (0.12)
	lnGFCF	-1.28** (0.04)	0.05 (0.93)	-0.40 (0.65)	-0.02 (0.87)	2.21* (0.00)	0.08*** (0.08)	-0.09 (0.85)
	lnLF	2.78* (0.00)	-2.50* (0.00)	0.18 (0.93)	1.67* (0.00)	-1.34 (0.31)	-0.42* (0.00)	9.05* (0.00)
	lnCTO	-0.04 (0.45)	0.01 (0.90)	0.89 (0.26)	0.05 (0.66)	-0.25 (0.23)	-0.08* (0.00)	0.08 (0.19)

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

mixed results imply that infrastructure development can have a dual impact on emissions, depending on the energy intensity of projects and the framework for urban expansion. Similarly, lnMKS also shows a dual impact, with a significant effect on lnCO2 only in Indonesia and Vietnam. In Indonesia, it has a negative coefficient, while in Vietnam, it has a positive coefficient. These results imply that market sophistication can influence emissions differently across countries, depending on the structure of economic activities, regulatory policies, and the adoption of sustainable market practices. Lastly, lnCTO is found to have a significant impact on lnCO2 only in the Philippines, with a negative coefficient. This indicates that creative outputs in the Philippines may contribute to lower carbon emissions, potentially through advancements in sustainable innovations.

In general, the country-specific GLM results indicate a positive influence of GII metric categories, reflecting similar evidence found in the panel dataset results. This suggests that the overall innovation ecosystem in SEA is still not conducive and plays a crucial role in shaping carbon emissions, emphasizing the importance of tailored policies to balance economic growth with environmental sustainability. Moreover, these findings highlight the need for region-specific innovation strategies that foster green technologies and sustainable practices to mitigate environmental degradation.

4.4.2. Robustness Check with RLS Estimation

Similar to the panel analysis, the study also conducts a robustness check for GLM results using RLS for country-specific analysis. Consistent with the GLM findings, the RLS results in Table 7 exhibit a similar pattern. The lnINS variable has a significant impact on lnCO2 in Singapore and the Philippines, with a positive coefficient, while lnHCR is significant in Indonesia, Singapore, Vietnam, and Cambodia, with a negative coefficient. Furthermore, lnIFR is significant with a positive coefficient in Thailand, with additional findings in Indonesia also showing a significant positive impact, while in Vietnam, it is significant with a negative coefficient. The lnMKS variable is significantly negative in Indonesia, but in Vietnam, its previously positive coefficient is no longer significant due to a p-value exceeding 0.1.

Interestingly, while lnCTO remains significantly negative in the Philippines, the RLS results reveal additional significant impacts in Indonesia, Singapore, and Cambodia. In Indonesia, it has a negative coefficient, whereas in Singapore and Cambodia, the coefficient is positive. Overall, similar to the GLM country-specific analysis, the RLS results generally show a positive coefficient for GII metric categories toward lnCO2, confirming that the overall innovation ecosystem in SEA

Table 7. Results of country-specific RLS estimation.

Model	Variable	Coeff. (Prob.)						
Dependent: lnCO2		*Indonesia*	*Thailand*	*Singapore*	*Malaysia*	*Vietnam*	*Philippines*	*Cambodia*
INS Model	C	-48.1* (0.00)	61.4* (0.00)	31.4*** (0.09)	0.21 (0.90)	5.29 (0.81)	-5.21* (0.00)	-79.7* (0.00)
	lnGDP	0.29 (0.34)	0.30 (0.50)	-0.11 (0.85)	-0.41 (0.17)	-0.53 (0.63)	1.01* (0.00)	-1.61 (0.21)
	lnGFCF	-1.11* (0.00)	-0.14 (0.79)	-0.47 (0.58)	0.02 (0.85)	1.59*** (0.09)	0.14* (0.00)	-0.07 (0.90)
	lnLF	4.79* (0.00)	-2.65* (0.00)	-3.12 (0.23)	1.79* (0.00)	-0.76 (0.60)	-0.38* (0.00)	8.50* (0.00)
	lnINS	0.01 (0.88)	-0.05 (0.41)	10.6*** (0.07)	-0.05 (0.79)	0.37 (0.22)	0.06** (0.01)	0.12 (0.61)
HCR Model	C	-28.8* (0.00)	62.9* (0.00)	32.9*** (0.06)	1.02 (0.53)	21.2 (0.30)	-4.43* (0.00)	-82.9* (0.00)
	lnGDP	-0.29 (0.42)	0.27 (0.54)	-0.16 (0.83)	-0.27 (0.36)	-2.24** (0.03)	1.03* (0.00)	-1.05 (0.30)
	lnGFCF	0.48 (0.19)	-0.13 (0.80)	0.17 (0.82)	-0.01 (0.95)	3.17* (0.00)	0.14* (0.00)	-0.32 (0.52)
	lnLF	2.30* (0.00)	-2.70* (0.00)	-0.50 (0.79)	1.59* (0.00)	-1.21 (0.39)	-0.46* (0.00)	8.29* (0.00)
	lnHCR	0.40* (0.00)	-0.04 (0.57)	-1.79* (0.00)	-0.19 (0.16)	-0.38*** (0.07)	0.02 (0.22)	-0.21* (0.00)
IFR Model	C	-54.9* (0.00)	55.4* (0.00)	53.9 (0.22)	-0.37 (0.92)	18.2 (0.37)	-5.05* (0.00)	-77.1* (0.00)
	lnGDP	0.67* (0.00)	0.26 (0.45)	2.12 (0.23)	-0.42 (0.18)	-2.01*** (0.05)	1.09* (0.00)	-1.97 (0.21)
	lnGFCF	-2.08* (0.00)	-0.66 (0.16)	-1.57 (0.33)	0.04 (0.81)	3.19* (0.00)	0.11*** (0.09)	0.11 (0.89)
	lnLF	5.92* (0.00)	-1.54*** (0.05)	-3.94 (0.35)	1.81* (0.00)	-1.38 (0.33)	-0.46* (0.00)	8.64* (0.00)
	lnIFR	0.23* (0.00)	0.26* (0.00)	1.51 (0.24)	-0.02 (0.89)	-0.53** (0.02)	-0.01 (0.80)	0.09 (0.80)
MKS Model	C	-19.8* (0.00)	59.4* (0.00)	-12.1 (0.69)	0.32 (0.87)	6.24 (0.76)	-5.39* (0.00)	-80.2* (0.00)
	lnGDP	0.56 (0.12)	0.10 (0.83)	0.49 (0.57)	-0.43 (0.18)	0.18 (0.89)	1.07* (0.00)	-1.75 (0.17)
	lnGFCF	0.18 (0.63)	0.09 (0.86)	0.40 (0.70)	0.03 (0.76)	1.17 (0.26)	0.11** (0.03)	-0.01 (0.99)
	lnLF	1.17** (0.04)	-2.59* (0.00)	0.04 (0.98)	1.79* (0.00)	-1.24 (0.36)	-0.41* (0.00)	8.66* (0.00)
	lnMKS	-0.54* (0.00)	0.04 (0.65)	1.42 (0.33)	-0.02 (0.85)	0.29 (0.10)	0.02 (0.55)	0.09 (0.37)
CTO Model	C	-50.6* (0.00)	59.7* (0.00)	75.4* (0.00)	-0.57 (0.79)	17.4 (0.41)	-4.97* (0.00)	-98.1* (0.00)
	lnGDP	-0.17 (0.58)	0.19 (0.70)	2.34* (0.00)	-0.26 (0.57)	-1.24 (0.18)	1.09* (0.00)	-0.24 (0.17)
	lnGFCF	-0.81* (0.00)	0.01 (0.99)	-2.10* (0.00)	-0.02 (0.89)	2.31* (0.00)	0.09 (0.10)	-0.84* (0.00)
	lnLF	5.21* (0.00)	-2.59* (0.00)	-4.79* (0.00)	1.63* (0.00)	-1.28 (0.38)	-0.41* (0.00)	8.69* (0.00)
	lnCTO	-0.08* (0.00)	0.01 (0.89)	1.46* (0.00)	0.05 (0.67)	-0.23 (0.32)	-0.07** (0.04)	0.14* (0.00)

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

is still not conducive to reducing emissions and plays a concerning role in shaping carbon emissions.

5. Discussion

The findings from both the panel and country-specific analyses provide meaningful perspectives into the relationships between various indicators of the innovation ecosystem and CO_2 emissions in the SEA region. The results reveal significant patterns that highlight the concerning impact of institutional factors, human capital, infrastructure, market sophistication, and creative outputs on rising carbon emissions.

The institutional category demonstrates a strong positive relationship with CO_2 emissions, suggesting that improvements in institutional metrics are linked to higher CO_2 emissions. This finding is particularly relevant in the SEA context, where rapid economic development often coincides with institutional reforms [115, 116]. As countries enhance their governance and regulatory frameworks, they may inadvertently promote industrial growth and energy consumption, leading to increased emissions [94, 95, 117]. This underscores the need for sustainable institutional practices that balance economic growth with environmental responsibility.

Similarly, the human capital and research category exhibits a general positive relationship with CO_2 emissions, especially in the panel analysis, indicating that higher levels of human capital and research can contribute to increased emissions. In the SEA region, as education and research capabilities improve, industrial activity and energy demand often rise in parallel [13, 118]. While human capital is essential for driving innovation and economic progress [119, 120], it is crucial to align these advancements with sustainable practices to mitigate their environmental impact. However, the country-specific analysis presents a more nuanced picture, showing that in some nations, improvements in human capital and research can help reduce CO_2 emissions, potentially due to advancements in green technologies or more efficient resource utilization [33, 67, 121].

Infrastructure development also emerges as a key factor influencing carbon emissions. In many SEA countries, enhanced infrastructure facilitates greater energy consumption and industrial output, leading to higher emissions [122, 123]. While infrastructure is critical for economic growth and improving living standards, prioritizing sustainable energy sources and environmentally friendly technologies is essential to minimizing the ecological footprint [124, 125]. Policymakers should focus on integrating green infrastructure solutions, such as energy-efficient transportation systems and renewable energy investments, to ensure that development does not come at the cost of environmental degradation [126, 127].

Market sophistication follows a similar pattern, showing a positive relationship with CO_2 emissions. As markets become more developed, they often drive increased consumption and industrial activities [128]. In the SEA region, this trend is evident as countries transition toward advanced economies with expanding trade, investment, and financial markets [129, 130]. However, it is crucial to ensure that market growth is accompanied by sustainable business practices, including green finance initiatives, circular economy models, and responsible consumption policies, to prevent further environmental deterioration [131, 132].

Lastly, the creative outputs category demonstrates a positive association with carbon emissions. The expansion of creative industries—such as media, design, entertainment, and digital content—may contribute to higher emissions through increased production, resource utilization, and consumption [133, 134]. While fostering creativity and innovation is essential for economic diversification and cultural development, integrating sustainability into these sectors is imperative [75, 135]. Encouraging eco-friendly production techniques, digital transformation, and sustainable content creation can help mitigate the environmental impact while ensuring the creative economy remains a driver of both growth and sustainability [45, 136].

Overall, the analysis highlights the intricate relationships between various GII metric categories and CO_2 emissions in the SEA region, with evidence pointing to a concerning conclusion regarding the role of the innovation ecosystem in balancing economic growth and environmental sustainability. As countries strive for economic development, it is imperative to adopt sustainable practices that align institutional frameworks, human capital, infrastructure, market sophistication, and creative outputs with environmental goals. This approach will be essential for addressing the pressing challenges of climate change and ensuring a sustainable future for the region.

6. Conclusions and Recommendations

The study concludes its thorough analysis by revealing that the innovation ecosystem in SEA countries continues to drive an increase in carbon emissions. All GII metric categories—including institutional factors, human capital, infrastructure, market sophistication, and creative outputs—are found to contribute to rising CO_2 levels. While institutional improvements and market development foster economic growth, they often drive increased industrial activity and energy consumption, exacerbating emissions. Similarly, advancements in human capital and research, though vital for innovation, can elevate energy demand unless aligned with sustainable practices. Infrastructure development, essential for progress, also poses environmental risks without green investments. Even creative industries, while fostering economic diversification, contribute to emissions through resource-intensive production. These findings emphasize the urgent need for policies that integrate sustainability into all facets of innovation, ensuring that economic growth does not come at the cost of environmental degradation.

To mitigate the environmental impact of the innovation ecosystem in SEA countries, policymakers must integrate sustainability into institutional frameworks, human capital development, infrastructure planning, market sophistication, and creative industries. Strengthening institutional frameworks requires embedding environmental accountability into governance, enforcing carbon taxation and emission regulations, and integrating sustainability standards into business licensing. Human capital development should prioritize green education, research, and workforce reskilling programs that focus on renewable energy, sustainable manufacturing, and circular economy principles. Infrastructure investments must emphasize renewable energy expansion, green urban planning, and sustainable transportation, including incentives for electric vehicles and smart grids. Additionally, promoting a circular economy through waste-to-energy initiatives and resource-efficient technologies can significantly reduce carbon footprints.

Market sophistication should align with sustainable growth by fostering green financing mechanisms, promoting responsible consumer behavior, and supporting environmentally conscious supply chains. Financial institutions should offer preferential loans and investment opportunities for businesses adopting sustainable practices, while corporations should integrate ESG (Environmental, Social, and Governance) considerations into their operations. The creative industries also need to embrace sustainability through eco-friendly production methods, digital content that promotes environmental awareness, and carbon-conscious event planning. By embedding sustainability across all facets of innovation, SEA countries can balance economic growth with environmental responsibility, ensuring long-term prosperity without exacerbating climate challenges.

Despite its evidence-based insights, this study has limitations. First, its focus on SEA countries limits generalizability; future research should include diverse economies for comparative analysis. Second, static econometric methods capture associations but miss dynamic interactions; adopting models like panel VAR or GMM could improve accuracy. Lastly, the control variables align with endogenous growth theory but may overlook factors like geopolitics, environmental policies, and energy transitions. Expanding these variables would provide a more comprehensive understanding of innovation's impact on carbon emissions.

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