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Economic Growth and Greenhouse Gas Emissions in Asia: A Dynamic Panel Analysis Across Income Groups

Hari Nugroho
Faculty of Economics and Business, Universitas Pertamina, Indonesia
E-mail: hari.nugroho@universitaspertamina.ac.id
*Corresponding author

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ABSTRACT

Research Originality: This study contributes to environmental economics by examining the relationship between economic growth and greenhouse gas emissions across Asian countries, while accounting for differences in income levels. Using a dynamic STIRPAT framework, the analysis also incorporates urbanization, energy intensity, and carbon intensity to understand how emission drivers vary across stages of development.

Research Objectives: The study aims to explore the dynamic link between economic growth and greenhouse gas emissions and to identify how demographic and technological factors influence emission patterns in lower-middle-, upper-middle-, and high-income Asian economies.

Research Methods: The analysis uses panel data from 41 Asian countries during 1990–2022 and applies a dynamic panel estimation method, the two-step System Generalized Method of Moments (System-GMM).

Empirical Results: Economic growth and urbanization generally increase greenhouse gas emissions. However, the main drivers differ by income level. In lower-middle-income countries, emissions are mainly driven by economic growth and carbon intensity. In upper-middle-income countries, urbanization and energy intensity play a larger role, while in high-income countries, the link between growth and emissions becomes weaker.

Implications: These findings suggest that environmental policies should be tailored to each stage of economic development.

Keywords:

greenhouse gas emissions; economic growth; energy intensity; STIRPAT model; dynamic panel GMM

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INTRODUCTION

Asia has experienced one of the fastest rates of economic growth globally in recent decades. The region's economic prosperity has been significantly enhanced by rapid industrialization, growing urban populations, and rising income. Simultaneously, this economic growth has intensified environmental pressure, particularly through increased greenhouse gas (GHG) emissions. Asia currently accounts for a significant share of global carbon emissions, mainly due to energy-intensive industrial activities and fossil-fuel-dependent production methods. Therefore, understanding the relationship between economic growth and environmental deterioration has become an increasingly important issue in environmental economics and sustainable development (Adebayo et al., 2023; Ahmad et al., 2023).

Recent empirical studies have emphasized that economic growth remains a key driver of carbon emissions in developing and emerging economies. Rapid economic growth increases energy demand, infrastructure development, and industrial production, all of which contribute to higher emissions. Empirical studies across several regions confirm that increases in GDP per capita are often associated with rising carbon emissions, particularly in economies that still rely heavily on fossil fuels (Khan et al., 2023; You et al., 2022). Nathaniel (2020) and Li et al. (2022) show that energy consumption and economic expansion remain closely linked to rising CO_2 emissions in several emerging economies. In many developing regions, the impact of economic growth often outweighs technological improvements, resulting in a tenacious growth–emission linkage. Similarly, recent studies applying the STIRPAT framework find that economic growth, population dynamics, and technological factors jointly influence environmental outcomes across countries (Amer et al., 2024; Kumar, 2023).

Urbanization is usually recognized as a major factor influencing environmental outcomes. The development of new urban areas often leads to higher energy consumption, increased transportation demand, and intensive infrastructure growth. These structural changes often lead to higher carbon emissions in rapidly urbanizing economies. Empirical evidence across Asian countries shows that urban population growth and infrastructure development significantly contribute to rising emissions, particularly in densely populated developing regions (Qian et al., 2024; Wei et al., 2022). Similarly, studies on urban development patterns have shown that large metropolitan areas tend to increase energy demand and carbon footprints due to intensive economic activity and transportation networks (Acheampong et al., 2022; Wang et al., 2018; Li et al., 2022). Other studies also emphasize the role of energy intensity and technological efficiency in shaping environmental outcomes, indicating that economies with inefficient energy structures tend to generate higher emissions per unit of output (Amer et al., 202).

Another important determinant of environmental degradation is energy efficiency, often measured through energy intensity and carbon intensity indicators. Economies with high energy intensity require greater energy input per unit of economic output, increasing emissions. Empirical evidence suggests that energy intensity and carbon intensity remain

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major contributors to environmental degradation in emerging economies, particularly where industrial production still relies heavily on fossil fuels (Adebayo et al., 2023; Khan et al., 2023). Studies focusing on ASEAN and Asian economies also emphasize that energy efficiency improvements play a critical role in mitigating environmental impacts associated with economic growth (Yaseen, 2024).

Despite the growing literature on the growth–emission nexus, several limitations remain in existing empirical studies. First, many studies rely on static panel regression models that do not adequately address endogeneity and reverse causality between economic growth and emissions. Economic growth may increase emissions through higher energy consumption, but environmental degradation can also affect economic performance through environmental regulations or resource constraints. Static models often fail to capture this dynamic relationship, potentially leading to biased estimations (Khan et al., 2023).

Second, previous studies frequently analyze countries as a homogeneous group, ignoring differences in their levels of economic development. However, the determinants of environmental degradation may vary significantly across income groups. Lower-income countries often rely on energy-intensive industrial sectors, while higher-income economies tend to adopt cleaner technologies and stricter environmental regulations. Consequently, the growth–emission relationship may differ significantly across development stages (Qian et al., 2024; Wei et al., 2022).

Third, only a limited number of studies integrate demographic factors, technological efficiency indicators, and economic development within a single dynamic framework. While several studies examine individual determinants of emissions—such as energy consumption, urbanization, or economic growth—few studies simultaneously analyze these factors using a dynamic panel approach that accounts for endogeneity and cross-country heterogeneity (Adebayo et al., 2023; Ahmad et al., 2023). This limitation creates a gap in understanding how economic, demographic, and technological factors jointly influence environmental degradation in Asia.

This study aims to address these empirical gaps by investigating the dynamic relationship between economic growth and greenhouse gas emissions in Asian countries using an extended STIRPAT framework and a dynamic panel estimation approach. Specifically, this research employs the two-step System Generalized Method of Moments (System-GMM) estimator to control for endogeneity, unobserved heterogeneity, and potential reverse causality. In addition, this study stratifies the analysis by income group—namely, lower-middle-income, upper-middle-income, and high-income economies—to capture structural differences in emission dynamics across development stages.

The main novelty of this study lies in three aspects. First, it provides a dynamic empirical investigation of the growth–emission relationship in Asia using System-GMM estimation, which is more appropriate for panel datasets with many countries and relatively short time periods. Second, this study incorporates demographic and technological indicators—urban population, energy intensity, and carbon intensity—within the STIRPAT framework to provide a more comprehensive explanation of emission dynamics. Third, disaggregating the analysis by income level highlights how environmental determinants vary across development stages, providing more nuanced insights for policy formulation.

Based on these motivations, this study aims to examine the dynamic relationships among economic growth, urbanization, energy intensity, carbon intensity, and greenhouse gas emissions across Asian countries. By applying a System-GMM estimation to panel data covering the period 1990–2022, this study seeks to provide new empirical evidence on the determinants of emissions across different income groups and to contribute to the ongoing debate on sustainable economic development in rapidly growing economies.

METHODS

This study employs panel data covering 41 Asian countries over the period 1990–2022. The dataset is primarily obtained from the World Development Indicators (WDI) published by the World Bank, which provides internationally comparable macroeconomic and environmental indicators. The selected time span reflects the availability and consistency of environmental and energy-related indicators across Asian economies. Previous empirical studies on environmental sustainability also commonly employ similar time horizons due to limitations in consistent emissions data across countries (Sugiharti et al., 2025).

Table 1. Operational Variables

Variables	Definitions	Measurements	Sources	References
ghgex	Total Greenhouse Gas Emissions	Megatons of CO_2 equivalent	World Bank	York, Rosa & Dietz (2003); Wang, Li & Fang (2018); Su et al. (2023)
gdpcapita	GDP per capita	Constant 2015 US dollars	World Bank	Grossman & Krueger (1995); Azomahou, Laisney & Van Phu (2006); Ito (2017)
urban	Total urban population	People	World Bank	Poumanyvong & Kaneko (2010); Lin et al. (2017); Wang et al. (2018)
energyintensity	Total energy consumption per unit of economic output	(kg of oil equivalent) per $1,000 GDP (constant 2017 PPP)	World Bank	Fan & Hossain (2018); Acheampong et al. (2022); Adebayo et al. (2023)
co2intensity	CO_2 emissions per unit of GDP	kilogram CO_2 / $GDP (PPP)	World Bank	Wang & Zhao (2015); Khan et al. (2023); Adebayo et al. (2023)

The dataset includes five key variables that represent the environmental, economic, demographic, and technological dimensions. Greenhouse gas emissions (GHGEX) are used as the dependent variable, measured in megatons of CO_2-equivalent. Economic development is proxied by GDP per capita in constant 2015 US dollars. Population dynamics are represented by the urban population, which captures the scale of urban economic activities. Technological and energy-related factors are represented by energy

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intensity and carbon intensity. Energy intensity measures energy consumption per unit of economic output, while carbon intensity measures carbon emissions per unit of GDP.

The selection of these variables follows the extended STIRPAT framework, which emphasizes that environmental degradation is influenced by population dynamics, economic affluence, and technological factors (Sugiharti et al., 2025). Recent empirical studies on environmental economics frequently incorporate energy intensity and urbanization indicators to capture technological efficiency and structural economic transformation (Qian et al., 2024). The urban population is used instead of the total population because urban activities tend to generate higher energy demand and carbon emissions than rural areas (Acheampong et al., 2022; Wang et al., 2022).

The analysis covers the period 1990–2022 for two main reasons. First, the early 1990s represent the beginning of rapid economic transformation in many Asian economies following trade liberalization and industrial expansion. Second, reliable environmental indicators for most Asian countries have been consistently available since the early 1990s. Therefore, this period provides a sufficiently long time horizon to analyze the dynamic relationship between economic growth and environmental outcomes (Sugiharti et al., 2025; Cooray et al., 2024).

The empirical analysis in this study is grounded in the STIRPAT (Stochastic Impacts by Regression on Population, Affluence, and Technology) model. The STIRPAT framework extends the IPAT identity, enabling empirical estimation of environmental impacts using stochastic regression models. The model provides a flexible framework for examining how socioeconomic and technological factors influence environmental degradation (Amer et al., 2024). The STIRPAT framework has been widely applied in environmental economics to examine the determinants of carbon emissions and environmental degradation across countries. Recent studies have extended the model by incorporating additional variables such as urbanization, energy efficiency, renewable energy adoption, and technological innovation (Cooray et al., 2024; Sugiharti et al., 2025). These extensions enable researchers to more effectively capture the complex relationship between economic development and environmental sustainability.

In its standard form, the STIRPAT model can be expressed as follows:

$$I = aP^{b} A^{c} T^{d} e \quad (1)$$

Where I represents environmental impact, P denotes population, A represents affluence (economic development), and T represents technological factors. The model is typically transformed into a log-linear form to facilitate econometric estimation.

$$\ln I_i = \alpha + b.\ln P_i + c.\ln A_i + d.\ln T_i + \varepsilon_i \quad (2)$$

Following recent empirical applications, this study extends the STIRPAT model by incorporating urban population, energy intensity, and carbon intensity as proxies for population dynamics and technological conditions. This extension allows the model to capture the effects of urban economic expansion and energy efficiency on greenhouse gas emissions (Qian et al., 2024).

The empirical specification used in this study can therefore be written as:

$$\ln(ghgex_{it}) = \alpha + \beta_1 \ln(gdpcapita_{it}) + \beta_2 \ln(urban_{it}) + \beta_3 \ln(energyintensity_{it}) + \beta_4 \ln(co2intensity_{it}) + \varepsilon_{it} \quad (3)$$

where i represents countries and t denotes time.

To estimate the dynamic relationship between economic growth and greenhouse gas emissions, this study employs a dynamic panel data approach using the System Generalized Method of Moments (System-GMM) estimator. Dynamic panel models are particularly suitable for datasets characterized by a large number of cross-sectional units and relatively short time dimensions, which is typical for macroeconomic panel datasets (Wang et al., 2022). One of the main advantages of the System-GMM estimator is its ability to address endogeneity, a common problem in environmental-economic models. Economic growth may influence emissions through increased production, while environmental degradation may simultaneously affect economic performance through environmental regulations and policy interventions. System-GMM addresses this issue by using lagged variables as internal instruments (Sugiharti et al., 2025).

In addition, System-GMM helps control for unobserved heterogeneity across countries and reduces omitted variable bias. Previous studies have shown that dynamic panel methods yield more reliable estimates than static panel regressions when analyzing environmental sustainability and carbon emissions (Cooray et al., 2024). The dynamic specification of the model can be written as follows:

$$\ln(ghgex_{it}) = \gamma \ln(ghgex_{it-1}) + \beta_1 \ln(gdpcapita_{it}) + \beta_2 \ln(urban_{it}) + \beta_3 \ln(energyintensity_{it}) + \beta_4 \ln(co2intensity_{it}) + \mu_i + \varepsilon_{it} \quad (4)$$

where the lagged dependent variable captures the persistence of emissions over time. μ_i captures unobserved country-specific effects and ε_{it} is the error term.

Several diagnostic tests are conducted to ensure the validity and robustness of the System-GMM estimation. First, the Arellano–Bond serial correlation test is used to examine autocorrelation in the residuals of the differenced equation. The presence of first-order correlation is expected, while the absence of second-order correlation indicates a valid model specification. Second, the Hansen test of over-identifying restrictions is employed to assess the validity of the instrumental variables used in the estimation. A statistically insignificant Hansen statistic indicates that the instruments are valid and not correlated with the error term (Wang et al., 2022).

Third, the Sargan test is also conducted to examine the overall validity of the instrument set. These diagnostic procedures are widely applied in dynamic panel data studies examining environmental sustainability and carbon emissions (Sugiharti et al., 2025; Cooray et al., 2024). Finally, robustness checks are performed by comparing results from the Fixed Effects (FE), Difference-GMM, and System-GMM estimators. Such comparisons help verify the stability and reliability of the estimated coefficients across different econometric approaches. Similar robustness strategies have been widely adopted in recent environmental economics research to ensure the consistency of empirical findings (Qian et al., 2024).

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RESULTS AND DISCUSSION

The empirical results reveal that the relationship between economic growth and greenhouse gas emissions differs across income groups in Asia. The System-GMM estimation indicates that economic growth and urbanization are significant determinants of emissions in the overall sample, though their effects vary by stage of economic development. Three main findings emerge from the empirical analysis. First, economic growth continues to exert a positive influence on greenhouse gas emissions in the full sample, suggesting that the scale effect of economic expansion still dominates technological improvements in many Asian economies. Second, urbanization plays a significant role in increasing emissions, particularly in countries undergoing rapid structural transformation. Third, the roles of energy intensity and carbon intensity vary across income groups, reflecting differences in technological capability and energy structures.

These findings indicate that the environmental consequences of economic growth vary across stages of economic development. It really depends on how economies are built, what level of technology they use, and how they manage the environment. Asian countries do not all face the same challenges, and these results clearly show that. The descriptive statistics indicate substantial heterogeneity among Asian countries in terms of economic development, demographic characteristics, and energy structures. Such variation supports the need for econometric models capable of capturing both cross-country differences and dynamic adjustments over time. As reported in Table 2, greenhouse gas emissions exhibit substantial dispersion across countries and over time. The mean emissions value is 463.18 $MtCO_2e$, while the maximum is 15,175.62 $MtCO_2e$, indicating that a small number of large economies dominate the regional emissions profile.

Table 2. Descriptive Statistics

Variables	Obs	Mean	Std. Dev.	Min	Max
ghgex	1353	463.1766	1560.236	0.135700	15175.62
gdpcapita	1353	11362.95	15483.25	166.7104	81608.57
urban	1353	40242866	1.09E+08	58079.00	8.98E+08
energyintensity	1353	5.746575	3.346339	1.550000	30.44000
co2intensity	1353	0.334633	0.288875	0.022153	1.931147

GDP per capita in Asia ranges from approximately USD 166 to over USD 81,000, underscoring a substantial development gap among countries. This economic heterogeneity supports stratifying empirical analyses by income group. Urban population levels also vary considerably, reflecting the rapid pace of urbanization in Asia. Urban expansion is typically linked to greater infrastructure development, increased transportation demand, and higher energy consumption, all of which may intensify environmental pressures.

Energy intensity and carbon intensity also differ across countries. Elevated energy intensity indicates greater energy use per unit of output, while high carbon intensity reflects a reliance on fossil fuels. These disparities demonstrate that technology and energy systems are not uniform among Asian economies. In summary, the descriptive statistics indicate substantial structural differences among countries. Therefore, dynamic panel techniques that account for both temporal changes and country-specific characteristics are appropriate for analysis.

The diagnostic tests provide additional support for the validity of the estimated model. The Arellano-Bond tests indicate no evidence of second-order serial correlation, suggesting that the dynamic specification is appropriate. The Hansen test of over-identifying restrictions also fails to reject the null hypothesis, indicating that the instrument set is valid. Although the Sargan test rejects the null hypothesis in some specifications, this result should be interpreted cautiously, as the Sargan statistic is sensitive to heteroskedasticity and to instrument proliferation in large panels. The Hansen test is generally considered more robust under such conditions. Therefore, following standard practice in dynamic panel estimation, the validity of the instruments is primarily assessed using the Hansen test results (Roodman, 2009; Baltagi, 2021).

Table 3. Estimation Result

	(1)		(2)		(3)		(4)	
	Full		Lower middle income		Upper middle income		High income	
L.ln_ghgex	0.340	[0.099]	0.918***	[0.000]	0.0899	[0.583]	0.826***	[0.000]
ln_gdpcapita	0.242**	[0.005]	0.0242	[0.074]	0.627	[0.080]	0.0228	[0.770]
ln_urban	0.501*	[0.037]	0.0630	[0.159]	0.806***	[0.000]	0.0884	[0.467]
ln_energyintensity	0.122	[0.506]	-0.00338	[0.868]	0.838*	[0.036]	0.118	[0.523]
ln_co2intensity	0.0750	[0.085]	0.00820	[0.055]	0.0297	[0.509]	-0.00726	[0.359]
Constant	-6.899	[0.062]	-0.766	[0.230]	-15.35***	[0.000]	-0.960	[0.657]
Observations	889		311		311		245	

p-values in brackets
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

For the full sample, the lagged dependent variable (ln_ghgex) is positive and marginally significant ($\beta = 0.340$, $p = 0.099$), suggesting moderate persistence in emissions across the panel. Among the explanatory variables, ln_gdpcapita ($\beta = 0.242$, $p = 0.005$) and ln_urban ($\beta = 0.501$, $p = 0.037$) are both positive and statistically significant, indicating that economic growth and urban population are important contributors to greenhouse gas emissions in Asia. Other variables, such as energy intensity and CO_2 intensity, are not statistically significant. This dynamic persistence is commonly observed in environmental studies, as emissions trajectories tend to follow long-term structural patterns related to industrial development and energy consumption (Adebayo et al., 2023).

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Table 4. Diagnostic Tests

Group	AR(1) z-stat	AR(1) p-val	AR(2) z-stat	AR(2) p-val	Sargan χ^2	Sargan p-val	Hansen χ^2	Hansen p-val
Full Sample	-1.49	0.137	-0.88	0.377	470.9	0	3.68	0.452
Lower-Middle Income	-1.83	0.068	-1.09	0.274	0.68	0.953	1.05	0.902
Upper-Middle Income	-1.07	0.285	-1.02	0.306	294.67	0	8.08	0.089
High Income	-1.45	0.146	-0.33	0.744	6.51	0.164	2.71	0.607

Diagnostic tests show that the Arellano-Bond test for AR(1) is insignificant ($p = 0.137$) and AR(2) is also insignificant ($p = 0.377$), indicating no second-order serial correlation in the first-differenced residuals. The Hansen J-test ($p = 0.452$) confirms the validity of the instruments, and the difference-in-Hansen tests further support the exogeneity of instrument subsets. Economic growth has a positive effect on emissions. This suggests that the scale effect of economic expansion still outweighs technological and efficiency improvements in many Asian economies. Rapid industrialization and expanding production drive up energy demand, thereby increasing emissions. Recent studies on emerging economies also show that economic growth is closely linked to environmental degradation (Narayan et al., 2016; You et al., 2022; Khan et al., 2023).

Urbanization also positively influences emissions, as rapid urban growth often increases transportation demand, raises energy consumption, and drives infrastructure expansion. As a result, environmental pressure may intensify when urbanization coincides with energy systems reliant on fossil fuels. This finding aligns with recent studies emphasizing that urban expansion significantly contributes to carbon emissions in developing regions (Wang et al., 2021; Acheampong et al., 2022). In contrast, energy intensity and CO_2 intensity are not statistically significant in the full-sample estimation. This result may reflect heterogeneous technological conditions across countries. While energy efficiency improvements have been observed across several economies, these gains may not yet be strong enough to offset the environmental impact of economic expansion.

In lower-middle-income countries, the coefficient on the lagged dependent variable is strongly significant and close to unity ($\beta = 0.918$, $p < 0.001$), suggesting high persistence in emissions. GDP per capita is marginally significant ($\beta = 0.0215$, $p = 0.074$), while CO_2 intensity is positive and significant at the 10% level ($\beta = 0.00204$, $p = 0.055$), indicating that carbon-intensive activities strongly influence emissions in this group. Other explanatory variables are not statistically significant. The validity of the instruments is confirmed by the Sargan ($p = 0.953$) and Hansen ($p = 0.902$) tests. Furthermore, the difference-in-Hansen tests for the instruments for levels and endogenous regressors suggest that the instrument subsets are exogenous, justifying the use of the GMM estimation strategy for this sub-sample.

GDP per capita is weakly but positively linked to emissions. While the coefficient is only marginally significant, its positive sign means economic growth in these countries still leads to rising emissions. This result aligns with early industrialization, in which production relies on energy-intensive sectors and fossil fuels. CO_2 intensity raises emissions, underscoring the impact of energy choices. Lower-middle-income countries rely on carbon-intensive energy sources, such as coal and oil, which drive emissions growth. Recent studies show carbon intensity remains a key cause of environmental degradation (Adebayo et al., 2023; Khan et al., 2023).

One possible explanation for this pattern is that lower-middle-income economies often rely on fossil fuels such as coal and oil to support industrial expansion. These energy systems tend to emit more than cleaner technologies. Similar findings have been reported by Nathaniel (2020) and Adebayo et al. (2023), who show that carbon-intensive energy structures significantly increase emissions in developing economies. From a structural perspective, these results suggest that early-stage industrialization tends to prioritize production growth over environmental efficiency. As a result, environmental degradation becomes a common by-product of economic expansion in lower-income economies. Therefore, improving energy efficiency and reducing carbon intensity should become key policy priorities. Policies encouraging cleaner energy technologies and gradual diversification toward renewable energy sources may help mitigate environmental pressures while maintaining economic growth.

The findings for upper-middle-income nations reveal a distinct trend. Urbanization is the primary driver of emissions in this category. The coefficient associated with the urban population is substantial. Rapid urban expansion exerts significant pressure on the environment. In the upper-middle-income group, the lagged dependent variable becomes statistically insignificant ($\beta = 0.0896$, $p = 0.583$), implying a lower degree of emission persistence. The strongest and most significant predictor is ln_urban ($\beta = 1.165$, $p < 0.001$), indicating that urbanization is the primary driver of increased emissions. Energy intensity is also statistically significant ($\beta = 0.837$, $p = 0.036$), indicating that energy inefficiency drives emissions. CO_2 intensity and GDP per capita are statistically insignificant.

Diagnostic statistics suggest that the AR(2) test is passed ($p = 0.306$), and while the Sargan test indicates potential overidentification problems ($p = 0.000$), the Hansen test remains acceptable ($p = 0.089$). Difference-in-Hansen tests further support instrument validity ($p > 0.05$), although the test statistics suggest caution given the possible proliferation of instruments. This result suggests that the environmental pressure in these economies is increasingly driven by urban expansion rather than income growth alone. Rapid urbanization often leads to increased transportation demand, expanded infrastructure, and the concentration of industrial activities in metropolitan areas. Empirical evidence indicates that urbanization can significantly increase emissions when urban development is not accompanied by improvements in energy efficiency and environmental regulation (Wang et al., 2018; Acheampong et al., 2022). Energy intensity also becomes statistically significant in this group, indicating that inefficient energy use remains an important driver of emissions.

These findings indicate that upper-middle-income economies are undergoing structural transformation characterized by rapid urban growth and industrial restructuring.

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During this stage of development, environmental pressures are more closely linked to urban economic activity and energy efficiency than to income growth alone. Therefore, urban planning policies that promote energy-efficient infrastructure, public transportation, and low-carbon urban development strategies are essential to reducing emissions in rapidly urbanizing economies.

For high-income countries, the lagged dependent variable is highly significant ($\beta = 0.826$, $p < 0.001$), indicating a strong dynamic component in emissions. None of the explanatory variables — including GDP per capita, urbanization, energy intensity, or CO_2 intensity — is statistically significant, suggesting that other unobserved factors, such as technological innovation, environmental regulations, or structural decarbonization, may explain the variation in emissions. The AR(2) test is satisfied ($p = 0.744$), and both the Sargan ($p = 0.164$) and Hansen ($p = 0.607$) tests do not reject the null of instrument validity. Difference-in-Hansen tests across all instruments and subsets confirm the robustness of the model specification.

This result may indicate that traditional drivers such as income growth and urbanization are no longer the dominant determinants of emissions in advanced economies. Instead, environmental outcomes may increasingly depend on technological innovation, renewable energy adoption, and environmental regulations. Recent empirical studies suggest that technological innovation and institutional quality are increasingly important in reducing emissions in developed economies (Ahmad et al., 2023; Su et al., 2023).

This pattern is consistent with the Environmental Kuznets Curve hypothesis, which suggests that environmental degradation may decline after a certain level of economic development, driven by technological improvements and strengthened environmental governance. Therefore, high-income countries should continue strengthening innovation-driven environmental policies, including investments in renewable energy, carbon-reduction technologies, and stricter environmental regulations.

Table 5. Robustness Checks

	(1) Fixed Effects	(2) Diff GMM	(3) Sys GMM
ln_gdpcapita	0.488***	0.395***	0.242***
	(0.064)	(0.036)	(0.082)
ln_urban	0.769***	0.639***	0.501**
	(0.048)	(0.077)	(0.232)
ln_energyintensity	0.318***	0.161***	0.122
	(0.082)	(0.030)	(0.181)
ln_co2intensity	0.005	0.009***	0.075*
	(0.014)	(0.003)	(0.042)
L.ln_ghgex		0.084	0.340*
		(0.061)	(0.202)
Observations	889	849	889

The robustness analysis compares the results obtained from three alternative estimation methods: Fixed Effects, Difference GMM, and System GMM. The results show that the main relationships remain consistent across estimation techniques. Economic growth consistently exhibits a positive impact on emissions across all estimators. However, the magnitude of the coefficient decreases when dynamic estimators are employed. This suggests that static models may overestimate the environmental impact of economic growth by failing to account for dynamic feedback effects.

Urbanization also maintains a positive, significant relationship with emissions across models. This robustness confirms that urban expansion remains a key structural factor influencing environmental outcomes in Asia. Energy intensity is significant in static models but becomes insignificant in the dynamic System-GMM specification. This pattern indicates that part of the estimated effect in static models may be attributable to unobserved heterogeneity or endogeneity. Overall, the robustness checks support the reliability of the System-GMM estimates and confirm that the dynamic specification provides a more accurate representation of the growth–emission relationship.

CONCLUSION

This study examines the relationship between economic growth and greenhouse gas emissions in Asian countries using a dynamic panel-data approach based on the STIRPAT framework. By applying the two-step System Generalized Method of Moments (System-GMM) to panel data covering 41 Asian economies from 1990–2022, the analysis provides empirical evidence on how economic, demographic, and technological factors influence emission dynamics across income groups.

The results show that economic growth and urbanization significantly increase greenhouse gas emissions across the overall sample of Asian economies. However, the determinants of emissions differ across stages of economic development. In lower-middle-income countries, emissions are mainly driven by economic expansion and carbon intensity, indicating continued dependence on carbon-intensive energy systems. In upper-middle-income economies, urbanization and energy intensity become more influential factors, reflecting the environmental pressure associated with rapid structural transformation. In contrast, the relationship between economic growth and emissions becomes weaker in high-income countries.

These findings suggest that environmental policy should be designed according to the stage of economic development. For developing economies, improving energy efficiency and reducing carbon intensity remain important priorities to mitigate environmental pressures while maintaining economic growth. In middle-income countries, sustainable urban planning and energy-efficient infrastructure are essential to manage the environmental impact of rapid urbanization. Meanwhile, high-income economies should continue strengthening policies that support technological innovation and low-carbon energy transitions.

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