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The Impact of Natural Resource Utilisation, Green Energy, Carbon Finance, Artificial Intelligence, and Sustainable Innovation on the Environment: Evidence from Asia

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With escalating global urgency surrounding environmental sustainability, Asian economies have intensified their efforts to improve environmental quality, particularly through reductions in carbon emissions. These have also been supported by the production of advanced technological solutions and the expansion of financial mechanisms dedicated towards environmental initiatives. Within this context, the present research empirically determines the impact of carbon finance, artificial intelligence, green energy, total natural resources, and sustainable innovation on environmental quality. A panel dataset covering three Asian countries is analysed by using advanced econometric techniques to ensure methodological robustness. The empirical outcomes show that carbon finance, green energy utilisation, and the integration of artificial intelligence, which exerts a positive and statistically significant effect on environmental quality, largely through reductions in CO2 emissions. In contrast, reliance on natural resources and higher economic growth are found to deteriorate environmental quality, whereas sustainable innovations show no significant relationship. These outcomes extend the existing literature by validating key determinants of environmental quality in Asian economies. Drawing on these insights, the research outlines policy implications to strengthen environmental performance in the countries under study.

Keywords: *Natural Resource Utilisation; Green Energy; Carbon Finance; Artificial Intelligence; Asia.*

Introduction

The utilisation of natural resources in both developed and developing countries is being rapidly depleted due to prevailing economic growth models and resource-intensive production systems. As per the UNEP (2021) report, global resource consumption is projected to triple by 2050, reaching approximately 140 billion tonnes of ores, fossil fuels, minerals, and biomass per year. Natural resources were a fundamental pillar of economic development because they serve as a significant input into industrial manufacturing and energy generation. Moreover, the availability of natural resources has long been associated with opportunities for economic progress. The unsustainable exploitation of these resources has raised serious concerns about environmental quality, ecosystem instability, and the long-term viability of economic growth (Chien et al., 2024; Mohd Rasid & Mahamad, 2014). A greater depletion of natural resources not only disrupts natural ecological cycles but also contributes to deterioration in environmental quality, thereby undermining global efforts to stabilise environmental and economic systems (Rao *et al.*, 2023; Lestari & Soewarno, 2024).

Environmental degradation has specific, severe implications for Asia, as the cost of declining environmental quality continues to rise. Regions' emerging economies face multiple interconnections among environmental challenges, including deteriorating air quality, declining forest cover, unmanaged land expansion, and water scarcity, which threaten food security, economic stability, and long-term development patterns (Tu, 2024). All these issues present "wicked problems" characterised by their complexity, dynamism, and resistance towards simple solutions. However, several Asian economies are focusing on sustainability agendas, yet the academic literature remains limited in identifying practical, technologically driven strategies that could effectively enhance environmental performance. The global energy system has undergone a fundamental transformation, with economies gradually shifting from fossil fuels to renewable energy. The transition necessitates a deeper examination of how technological advancements such as artificial intelligence (AI), carbon finance mechanisms, and sustainable innovations interact with natural resource utilisation to affect environmental results (Wang *et al.,* 2023). Current studies have shown the environmental effects of artificial intelligence that vary across industries and stages of economic development. The adoption of AI significantly reduced carbon intensity during China's 12th Five-Year Plan compared with the 11th, particularly in labour- and technology-intensive industries (Chang et al., 2023). Similarly, natural resource dependence has been linked to increased CO_2 emissions, giving rise to the "carbon curse," where resource-rich countries experience environmental decline due to unsustainable extraction practices (Ali *et al.,* 2022). In parallel, financial development, fintech, and economic expansion have shown mixed effects on environmental quality;. At the same time, these factors stimulate growth, but they may also exacerbate emissions unless accompanied by green innovation and environmentally conscious policymaking (Huang & He, 2023). These divergent findings highlight the need for empirical research that jointly analyses natural resource utilisation, technological progress, and financial mechanisms within an integrated framework. Studies on environmental sustainability has grown substantially, that different substantive gaps remains, first in most of studies there is an analysis of determinants of environmental quality such as financial development, renewable energy and innovation in isolation without considering their combined and interactive effects within Asian economies (Tu, 2024; Wang *et al.,* 2023; Du & Wang, 2025; Skare *et al.,* 2024). This fragmented approach limits complete understanding of how multiple environmental, financial and technological factors operate simultaneously. Second, there is limited empirical evidence on the combined influence of emerging technological forces when determined alongside natural resources utilisation. Third, sustainable innovation has been recognised as a potential mechanism for reconciling economic growth with environmental protection; its empirical role, whether as an independent factor or a mediating channel, remains underexplored (Li *et al.,* 2025). Finally, comparative panel-based analyses that integrate natural resources, financial tools, green energy transitions, and digital technologies into a unified empirical framework are scarce, resulting in limited evidence for region-specific policy recommendations.

Literature Review

Climate change has emerged as one of the most pressing challenges worldwide, with its influence increasingly evident in extreme weather events, rising global temperatures, intensifying forest fires, and frequent flooding (Masson-Delmotte & IPCC, 2021). All these shifts have been driven largely by human activities, which pose severe threats to ecosystems, economic systems, and human well-being. The central driver of these changes is the rapid increase in atmospheric CO2, primarily from fossil fuel combustion, industrial activity, and unsustainable resource use (Dong *et al.,* 2019). Because CO2 traps heat for hundreds to thousands of years, its accumulation in the atmosphere exerts long-term warming effects, making it the most reliable and direct indicator of anthropogenic climate change (Bazzaz, 1990; Masson-Delmotte & IPCC, 2021). The acknowledgement of the crisis's urgency at the 26th United Nations Climate Change Conference (COP26) culminated in the Glasgow Climate Pact, a global commitment to limit temperature rise to 1.5 °C and to move towards net-zero emissions (Lennan & Morgera, 2022). The effectiveness of pledges depends primarily on high-emission countries and larger corporations, making it imperative to understand the factors that shape regional and sectoral contributions to global carbon emissions. Across nations, individuals and firms can contribute to emission reduction through changes in lifestyle, consumption, technological adoption, and sustainable production practices (Balderjahn *et al.,* 2020; Thogersen, 2021; Zhang, 2024). Businesses specifically face increasing scrutiny of their emissions performance, particularly poor CO2 management, which is increasingly linked to reputational and financial risk (Gallo *et al.,* 2023; Xiao & Qu, 2025). In this context, Asia occupies a central and unique position in climate conversation. As home to more than half of the world's population, many of whom are highly vulnerable to climate risks such as rising sea levels and intensified heat waves, the region faces disproportionate environmental, economic and social challenges (Wong, 2022). The economic landscape of Asia has been stretched from industrial giants Japan and China to emerging economies in Southeast Asia, which have experienced rapid industrialisation, resource extraction, and technological advancements. However, these developments have significantly raised living standards while also accelerating deforestation, water scarcity, air pollution, and greenhouse gas emissions (Anderson et al., 2020). With balanced economic growth and ecological sustainability, it has become a basic imperative for governments, industries and communities across the region (Yang & Solangi, 2024; Che, 2025). Given the heterogeneity of Asia, sustainability strategies should consider each nation's developmental stage, technological capacity, and resource endowment (Saidani *et al.,* 2019). This study has conducted a multi-dimensional examination of how natural resource utilisation, green energy expansion, carbon finance mechanisms, artificial intelligence (AI), and sustainable innovation shape the environmental outcomes across Asian economies. However, previous studies have explored these areas independently; there remains limited evidence on how these components review and synthesise existing research to highlight current progress, identify gaps, and contextualise the current requirement for integrated policy and technological responses. The extraction and utilisation of abundant natural resources have heavily driven Rapid Asia's economic rise. The region is being endowed with some significant mineral reserves, fossil fuels, forests, and freshwater resources that fuel its industrial and agricultural development (Wang, Liang, & Shi, 2022). Intensive exploitation has caused severe ecological degradation. The deforestation, specifically in Malaysia and Indonesia, due to palm oil cultivation has destroyed crucial habitats, contributed to biodiversity loss, and weakened ecosystem resilience (Susanti & Maryudi, 2016; Brandão, Barata, & Nobre, 2022; Chen *et al.,* 2024). In China and India, industrial emissions and the use of fossil fuels have resulted in severe air pollution, which adversely affects human health and reduces life expectancy (Chen et al., 2023b). Waste disposal and improper mining practices have further contaminated water and soil systems, threatening the agricultural productivity and quality of freshwater (Mardonova & Han, 2023). Different Asian countries have introduced regulatory frameworks for mitigation of environmental damage such as China's tightening of coal regulations and India's national forest policy for their effectiveness that varies widely because of governance challenges, corruption, and gaps in technological capability (Chen et al., 2022; Sahana *et al.,* 2022; Tripathi, Shukla, & Patel, 2023; Mishchuk *et al.,* 2025; Khatami *et al.,* 2024). This requirement has underscored the need for a stronger institution, technological integration, and coordinated policy execution. Meeting these consequences of fossil fuel dependence, Asia has been rapidly turning to green energy. China has become the world's leader in solar and wind energy investments; however, India's National Solar Mission has aimed to transform its energy landscape with ambitious capacity targets (Li *et al.,* 2021; Elavarasan et al., 2020; Xuan et al., 2025). South Korea and Japan are shifting from nuclear and fossil fuels towards solar and offshore wind, and Himalayan nations like Nepal and Bhutan continue to rely heavily on hydroelectric power (Koo, 2023; Yangka, 2019). Southeast Asian countries, particularly Thailand and Indonesia, are expanding bioenergy production by utilising agricultural residues (Fungtammasan *et al.,* 2022; Bartuseviciene et al., 2025). Moreover, impressive progress in green energy growth faces structural challenges, less developed economies struggle with limited access to capital, insufficient manufacturing capacity for renewable technologies and outdated energy infrastructure incapable of supporting variable renewable inputs (Sim *et al.,* 2021; Behuria, 2020; Basit *et al.,* 2020). Successful initiatives, including China's large-scale solar farms (Shi et al., 2013), India's solar-powered rail networks (Kumar *et al.,* 2024), and the Philippines' offshore wind projects (Vazquez *et al.,* 2024), demonstrate the region's potential for large-scale green transformation.

Carbon financing has emerged as a crucial tool in Asia's approach to climate mitigation, enabling countries to reduce emissions from market-based mechanisms such as carbon trading, carbon taxes and green bonds. China launched the world's largest national carbon emissions trading system in 2021, which covers energy-intensive sectors such as power generation and heavy manufacturing (Sigov *et al.,* 2022). In Singapore, the carbon tax, introduced in 2019, sets a regional precedent, motivating firms to reduce emissions intensity and innovate low-carbon solutions (Quah & Tan, 2022). India and China have become leading issuers of green bonds to finance renewable energy projects. Energy efficiency programs and sustainable water systems (Zhao *et al.,* 2022). These financial mechanisms have demonstrated measurable environmental impact. Carbon trading schemes have encouraged Chinese companies to invest in cleaner technologies, while carbon taxation in Japan has accelerated energy efficiency improvements (Wang *et al.,* 2020; Fu *et al.,* 2023). Green bond proceeds have enabled large-scale renewable energy deployment in India, helping bridge financing gaps for sustainability-focused enterprises (Freytag, 2020). There is a rapid expansion of the digital era, big data and artificial intelligence (AI) that have emerged as significant tools for complex environmental challenges (Abdullahi *et al.,* 2024; Darwish & Bakar, 2018; Eweoya *et al.,* 2023; Lazarevska *et al.,* 2022; Sajid & Kavitha, 2024; Tu *et al.,* 2023; Wu *et al.,* 2022). Asian economies face mounting ecological pressures, specifically in relation to rising carbon emissions, inefficient natural resource utilisation, and the current requirement for sustainable development, traditional environmental management approaches that have become increasingly inadequate (Aziz *et al.,* 2024; Chen *et al.,* 2023a; Cunha *et al.,* 2022; van Klink *et al.,* 2022; Yan *et al.,* 2024). These limitations underscore the need for data-driven, intelligent, and technology-supported frameworks capable of improving environmental quality while supporting economic development. Recent empirical findings show that AI plays a complex role in reducing carbon intensity, with its environmental benefits becoming increasingly evident as countries advance technologically. For instance, during the transition from China's 11th and 12th five-year plans, AI significantly reduced carbon intensity, especially in labour- and technology-intensive industries (Chang et al., 2023). This shows that AI-driven systems, such as energy monitoring platforms, predictive emission models, and smart industrial optimisation, could substantially improve environmental performance in emerging Asian economies. Therefore, literature also points towards significant contradictions regarding the role of natural resources. However, natural resources can support economic development; resource-rich countries often suffer from higher CO2 emissions, a phenomenon widely described as the "carbon curse". The overexploitation and misuse of natural resources tend to exacerbate environmental degradation, which requires countries to develop effective de-cursing strategies and sustainable extraction policies (W. Ali, Gohar, Chang, & Wong, 2022). Within this context, the integration of carbon finance becomes crucial. Carbon finance mechanisms encourage the government and firms to adopt cleaner technologies and invest in low-carbon initiatives, thereby reducing the environmental externalities associated with resource exploitation. Traditional policy evaluates methods such as econometric models. Cost-benefit analyses and expert-based assessments that have been used to support environmental policy-making suffer from several shortcomings. These include a limited capacity model that involves complex interdependencies among ecological, economic, and climate factors, and insufficient tools for handling uncertain and spatial data (Cao & Jian, 2024; Wei *et al.*, 2024). These approaches often fail to fully capture the dynamic and multidimensional nature of environmental quality in developing countries. Machine-learning applications in natural resources research are growing; many existing and predictive models still struggle to account for multi-dimensional interactions among multiple environmental variables, which reduces accuracy and interpretability. Within these limitations, scholars have highlighted the significance of green energy adoption and sustainable innovation as a dual solution for environmental deterioration and economic development. Renewable energy use reduces carbon dioxide emissions while simultaneously supporting long-term industrial transformation (Huang & He, 2023). Consequently, sustainable innovation, specifically green technology innovation, plays a significant role in moderating the environmental quality, although empirical outcomes remain mixed regarding its immediate significance in some Asian contexts (Ceicyte-Pranskune, 2025).

The review of literature provided a detailed analysis of current trends in environmental improvement and identified areas that had gone unnoticed. A dynamic interplay between natural resource utilisation, green energy adoption, carbon finance mechanisms, the integration of artificial intelligence, and sustainable innovation provides a comprehensive review of environmental management strategies in Asia. Exacerbated by rapid economic development and urbanisation, these components collectively form the backbone of Asia's response to environmental challenges. The impact of utilising natural resources, green energy adoption, mechanisms linked to carbon finance, the role of artificial intelligence, and sustainable innovations across different Asian countries in meeting sustainability goals was covered. Certain gaps were identified during the literature review. Firstly, studies linking the integration of multiple sustainability strategies (such as green energy, AI, and carbon finance) across sectors, including agriculture, industry, and urban development, that evaluate the systemic impacts are needed. For the long-term tracking effects of sustainable innovations and carbon finance mechanisms on environmental and economic outcomes, there is a lack of longitudinal research. To highlight best practices and the contextual effectiveness of various approaches, comparative studies across different Asian countries are required. For adopting advanced technologies (including AI and renewable energy technologies) in less developed Asian economies, more research is needed on the barriers to and opportunities. Studies overlook the distinct impacts of small and large enterprises, including carbon taxes and green energy transitions. The social and behavioural aspects of sustainability transitions have gaps in understanding, such as research that could focus on role education, public perception, and behavioural-level changes towards sustainability. In real-world emission-reduction scenarios, there is a lack of quantitative models to assess the efficiency and effectiveness of carbon finance mechanisms. To mitigate the environmental footprint of AI technologies, detailed lifecycle assessments and strategies are needed, as research on their environmental impact is still nascent. There is a gap in comparative studies of adaptation strategies for green technologies across urban and rural settings. For fostering a more sustainable future, not only for the region but for the whole planet, future research can provide a more comprehensive understanding of how best to deploy these strategies within Asia and globally, with the help of addressing these gaps.

Methodology and Data

Data and Regression Model

The data for this study comprises countries in Asia, including China, India, and Indonesia. Therefore, this study considers a panel dataset of three countries. The dataset comprises indicators from 2000 to 2021 sourced from databases maintained by the World Bank, Our World in Data, and the Organisation for Economic Co-operation and Development (OECD). The research question proposed in the study leads to the construction of the following equation under the umbrella of the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT), proposed by (Dietz & Rosa, 1997). This model is intensively used in the existing literature to examine the impact of socioeconomic factors on environmental degradation. This model assumes that environmental consequences arise from the interplay of three main determinants: population, affluence, and technology. The basic form of the model is given as follows:

$$I_i = \alpha P_i^{\beta} A_i^{\gamma} T_i^{\delta} \varepsilon_i \quad (1)$$

Where I represents environmental impacts and P, A and T denote population, affluence and technology. Based on this model, we formulate the basic regression model as follows:

$$EQ_{it} = \beta_0 + \beta_1 SI_{it} + \beta_2 AI_{it} + \beta_3 EG_{it} + \beta_4 URB_{it} + \varepsilon_{it} \quad (2)$$

Where EQ represents environmental quality and measures the I (impact) component of the STIRPAT model, similarly, the T, A, and P components are measured by sustainable innovations (SI), artificial intelligence (AI), economic growth (EG), and urbanisation (URB), respectively. Moreover, based on the objectives of the study and support from existing literature, NR, CF and GE are added to the model, and the model of the study takes the following form:

$$EQ_{it} = \beta_0 + \beta_1 SI_{it} + \beta_2 AI_{it} + \beta_3 EG_{it} + \beta_4 URB_{it} + \beta_5 GE_{it} + \beta_6 CF_{it} + \beta_7 NR_{it} + \varepsilon_{it} \quad (3)$$

The above function represents the environment as EQ, which is the dependent variable. EQ is measured using carbon emissions, measured as metric tons per capita. Environmental quality is usually gauged using CO_2 emissions per capita (H. S. Ali *et al.*, 2019). NR depicts natural resource utilisation, which is assessed using the indicator "natural resource rents," as previously used in research (Shittu, Adedoyin, Shah, & Musibau, 2021). Natural resource rents are gauged as a proportion of the GDP. Data on CO_2 emissions and NR are taken from the World Development Indicators (WDI). GE exhibits green energy, which is cleaner energy and is measured as the percentage of renewable energy in total energy consumption. CF represents carbon finance, measured as international financial flows to developing countries for the generation of renewable and clean energy and for clean energy research and development (millions of US$). This data is taken from the Our World in Data database. AI refers to artificial intelligence and is measured by the number of patents related to it, collected from the OECD database. The variable SI measures the level of sustainable innovation as the percentage of patents in environmental-related technologies relative to total technologies. Data for sustainable innovation is also extracted from the OECD database. Lastly, EG shows economic growth, measured by GDP (Constant US$), and URB represents urbanisation, measured as the percentage of the urban population in the total population. The data for both variables are from the WDI database.

Econometric Strategy

The present study relies on advanced econometric techniques to provide a comprehensive analysis. The estimation of the long-run association between variables is conducted using advanced panel-data techniques. The analysis is conducted in the following steps.

Cross-Sectional Dependence Test

Firstly, cross-sectional dependence (CSD) is checked. Pesaran (2004) in the dataset, as it comprises three different countries. Testing for CSD is a crucial part of panel data analysis, as it can result in spurious regression estimates. (Ahmad et al., 2020). The presence of CSD in the dataset indicates that one country is affected by the internal or external shock of another. As countries are now economically and globally integrated, a shock in one country can affect the progress of others. Thus, it is essential to ensure that there is no CSD between the series with two hypotheses: the null hypothesis states that there is no CSD, and the alternative hypothesis assumes that there is CSD. The basic statistics of the test are given as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \sim N(0,1)i,j \qquad (2)$$

$\boldsymbol{\hat{\rho}_{ij}^{2}}$ shows the coefficient of pair-wise correlation.

Slope Heterogeneity Test

The second step involves testing slope homogeneity, as there is a probability of differences in cross-sectional factors across the cross-sectional units. For this purpose, we follow. Pesaran and Yamagata (2008) testing procedure. The null hypothesis of the test assumes homogeneity of slope parameters, implying that there is no difference in slope coefficients across cross-sectional units. In contrast, the alternative hypothesis posits heterogeneity in slope parameters. This approach applies to both unbalanced and balanced panel data, is robust to CSD and serially correlated errors, and supports weakly and strictly exogenous regressors. The basic test statistics are given as follows:

$$\tilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\tilde{S}-k}{\sqrt{2k}}\right) \qquad (5)$$

$$\tilde{\Delta}_{adj} = \frac{\sqrt{N}\left[N^{-1}\tilde{S}-E(\tilde{Z}_{it})\right]}{\sqrt{Var(\tilde{Z}_{it})}} \qquad (6)$$

where, $\tilde{\Delta}$ and $\tilde{\Delta}_{adj}$ represent delta and adjusted delta tilde, respectively.

Panel Unit Root Tests

In the third stage, after confirming the issues of CSD and heterogeneity in panel data, we conduct second-generation panel unit root analysis, as the first-generation panel unit root tests are not robust or efficient in the presence of these issues. Therefore, the second-generation Cross-sectional Augmented Dickey-Fuller (CADF) and Cross-sectional Im-Pesaran-Shin (CIPS) tests are applied to examine the stationarity of the data series. The basic statistics of the CADF test are written in the equation as follows:

$$\Delta y_{it} = \alpha_i + \rho_i^{*} y_{it-1} + d_0\bar{y}_{t-1} + \sum_{j=0}^{p} d_{j+1}\overline{\Delta y}_{t-j} + \sum_{k=1}^{p} c_k \Delta y_{it-k} + \varepsilon_{it} \qquad (7)$$

In the above equation, Δy_{it} shows the cross-sectional averages. The CIPS test statistics can be computed from these CADF statistics as follows:

$$\text{CIPS} = \frac{1}{N}\sum_{i=1}^{N} CADF_i \qquad (8)$$

Driscoll-Kraay Standard Error Approach

The fourth step in empirical analysis involves estimating the long-run relationship between the dependent and independent variables. For this estimation, the Driscoll and Kraay (DKSE) method is used in the present study, which was proposed by (Driscoll & Kraay, 1998). This approach is effective in the presence of the CSD, heterogeneity and autocorrelation issues. Also, this technique is applicable when data sets contain temporal and cross-sectional dependencies. This technique is mostly applied in models with fixed effects. (Sultana & Rahman, 2024). Since this approach addresses heteroscedasticity and CSD in the model and enables us to obtain more accurate estimators, the DKSE estimator is used to estimate the study model.

Method of Moments Quantile Regression (MMQR) for Robustness Check

In the final step of empirical estimation, the MMQR approach is used to conduct a robustness check of the DKSE estimates for the proposed model. This technique, similar to DKSE, overcomes the issues of CSD and heterogeneity in the panel data models. Furthermore, the MMQR approach captures the heterogeneous effects of the independent variables on the dependent variable because it provides results across different quantiles. (Salim Omar, Khalifa, & Kareem, 2025).

Empirical Results

Empirical estimation begins with descriptive statistics, which provide the basic characteristics of the data series, including the mean, standard deviation, and data range (i.e., minimum and maximum values). These summary statistics are given in Table 1. It can be observed that AI has the highest mean and standard deviation, while EQ has the lowest. The data range, i.e., the minimum and maximum values of the variables of interest, is also provided in the summary statistics.

Table 1

Descriptive Statistics

	EQ	**AI**	**NR**	**GE**	**SI**	**CF**	**EG**	**URB**
Mean	3.205	43.822	4.447	29.525	9.497	4.4408	3.6312	43.594
Std.Dev	2.546	124.70	2.764	11.674	2.835	5.2608	4.2812	10.438
Minimum	0.938	0.000	0.836	11.3	2.609	13000	3.9511	27.667
Maximum	8.936	644.5	11.125	47.1	017.141	2.4009	1.6213	62.512
Observations	66	66	66	66	66	66	66	66

Next, for the assessment of the CSD issue, Pesaran (2004) The test is applied. The findings, presented in Table 2, test the null hypothesis of cross-sectional independence. In this regard, the p-values in the table are statistically significant, leading to the rejection of the null hypothesis and the conclusion that CSD is present in the data.

Table 2

Results of CSD Test

Variables	**CD-test statistics**	**P-value**
EQ	7.689***	0.000
AI	4.692***	0.000
SI	1.804*	0.071
CF	3.432**	0.001
NR	6.267***	0.000
GE	6.543***	0.000
EG	8.103***	0.000
URB	8.1***	0.000

*Where ***, ** and * reveal significance at 1, 5 and 10%, respectively.*

Moreover, the model's suitability is assessed using the slope heterogeneity Test. The results are shown in Table 3. The p-values reported in the table are statistically significant. This implies that the null hypothesis cannot be rejected as the p-value is greater than 0.05. Hence, the slope heterogeneity is concluded in the model.

Table 3

Results of Slope Heterogeneity Test

Dependent variable: EQ	**Test statistics P-Value**
Delta tilde	2.684** (0.004)
Adjusted Delta tilde	3.726*** (0.000)

Where *** and ** show significance at 1 and 5%, respectively.

Another crucial test in panel data analysis is the assessment of the order of integration among the study's variables. This assessment is done using. Pesaran (2007) unit root tests named Cross-sectional ADF (CADF) and Cross-sectional IPS (CIPS). The results shown in Table 4 indicate that the series follow a mixed order of integration, as some variables are stationary at the first difference and others at the level.

Table 4

Results of Unit Root Tests

Variables	**CIPS**		**CADF**	
	Level	First difference	Level	First difference
EQ	-1.623	-2.828***	-2.451	-3.162***
CF	-3.829***	--------	-4.265***	---------
SI	-0.319	-3.644***	0.253	-3.706***
GE	0.013	-5.101***	-0.828	-3.104**
NR	-2.305*	--------	-1.729	-3.182**
AI	-3.483***	--------	-2.596*	--------
EG	0.699	-3.273***	-2.130	-3.273**
URB	1.152	-2.753***	1.014	-2.753**

*Where *** and ** show significance at 1 and 5 %, respectively.*

Table 5 displays the results of the DKSE approach, revealing the relationship between dependent and independent variables. The outcomes reported in the table below indicate that CF and EQ are positively related, and that CF has a significant negative impact on CO_2 emissions. A positive association between CF and EQ suggests that increasing CF leads to improved environmental quality. The coefficient is highly statistically significant, indicating that for a one-unit increase in CF, EQ improves by 1.84 units. This finding is in line with multiple earlier studies, such as Meo and Abd Karim (2022), Yadav, Gyamfi, Asongu, and Behera (2024) and (Umar & Safi, 2023). This implies that the carbon finance approach is effective in improving EQ because it serves two functions: guiding green investments and serving green industries. The finding also demonstrates that to achieve carbon neutrality targets, a guidance-oriented carbon finance method may provide an optimal allocation of capital and environmental resources, thereby encouraging carbon reduction and green economy transformation. (Tong, Yue, & Xue, 2022). Moreover, according to Khan et al., (2022) Green or renewable energy helps achieve environmental sustainability.

Table 5

Long Run Findings of DKSE Regression

Variables	Coefficients	Driscoll-Kraay Standard Error	P-value
AI	-0.0028**	0.007	0.002
NR	0.0661**	0.0188	0.002
GE	-0.0513***	0.0114	0.000
SI	-0.0076	0.0053	0.164
CF	-1.84e-10***	4.03e-11	0.000
EG	5.53e-13***	4.48e-14	0.000
URB	-0.0184	0.0263	0.492

Where *** and ** show significance at 1 and 5%, respectively.

Secondly, AI is also reported to have a positive effect on EQ, suggesting that increased AI reduces CO_2 emissions. The positive relationship between EQ and AI is significant at the 5% level. A one-unit increase in AI is associated with a 0.002-unit decline in CO2 emissions, according to the relevant coefficient. The finding aligns with Dong, Wang, and Han (2023), Zhong, Zhong, Han, Yang, and Zhang (2024) and Cao, Chi, and Shan (2025) who argued that AI significantly reduce CO_2 emissions. This finding indicates that AI technology drives routine-based and skill-based technological change, thereby advancing environmental sustainability. (Cao *et al.,* 2025). Moreover, according to Ding et al., (2023) AI reduces CO_2 emissions via structural and technical effects.

Third, the findings demonstrate a negative association between GE and CO_2 emissions. In other words, the finding implies that consuming GE leads to improvements in EQ. Regarding the size of the coefficient, a one-unit increase in GE is associated with a 0.0513-unit decline in CO_2 emissions. This finding is supported by Hanif, Nawaz, Hussain, and Bhatti (2022) and Usman (2023) The authors claimed a negative association between green or renewable energy and CO_2 emissions. Thus, the finding supports the notion that transitioning the energy system from non-renewable to green sources reduces carbon concentrations and improves EQ.

As the impact of SI on EQ is also analysed in the study, the findings reported in Table 5 demonstrate a positive association between SI and EQ, as the coefficient is negative, indicating that an increase in SI reduces CO_2 emissions. The negative impact implies that sustainable innovations help reduce energy consumption, which ultimately leads to improvements in EQ. (Y. Li, Zhang, Li, & Usman, 2022). However, this effect is statistically insignificant. Although this finding is unexpected, it aligns with Y. Li et al. (2022) and (Du, Li, & Yan, 2019). For the association between NR and EQ, Table 6 reports a negative association, as we find a positive relationship between NR and CO_2 emissions. The size of the coefficient indicates that for a 1% increase in NR, CO_2 emissions increase by 0.0661 units. This finding indicates that increasing utilisation of natural resources puts burden on the environment, as the exploitation of natural resources or their rent increases carbon emissions. (Zhang, Khan, & Zafar, 2022). As NR is the primary source of raw material and services to carry out economic activities, therefore, extraction, mining, processing, and depletion of NR degrade the environmental quality and increase CO_2 emissions (Amer, Meyad, Meyad, & Mohsin, 2024). This finding aligns with several previous studies including. Hanif, Nawaz, Fazal, and Ibraheem (2022), Amer et al. (2024) and (Baloch, Mahmood, & Zhang, 2019).

The coefficient for EG indicates a positive relationship with CO2 emissions, suggesting that higher CO2 emissions lead to deterioration in EQ. For one unit increase in EG, CO_2 emissions increase by 5.531 units. The main reason for this positive relationship between EG and CO_2 emissions is the consumption of fossil-fuel-based energy for industrial and agricultural activities, which drive high economic growth but lower environmental sustainability. (Bilal, Li, Zhu, Sharma, & Jahanger, 2021). From earlier studies, this outcome is supported by several studies, including. Onofrei, Vatamanu, and Cigu (2022), Raihan (2023) and (Liu *et al.,* 2023). Last, the URB variable is estimated to be affecting CO_2 emissions positively but insignificantly, in line with the outcomes of R. Ali, Bakhsh, and Yasin (2019) and (Liao *et al.,* 2024).

To check the robustness of the long-run estimates, we re-estimate the model using the panel MMQR approach. The findings from the robustness analysis are given in Table 6. The similarity in sign and significance of the regression estimates (although their magnitudes differ) confirms the robustness of the DKSE estimation considered in the present study.

Table 7

Robustness Check using MMQR Regression

Dependent variable: CEM										
Series	Location	Scale	Quantiles							
			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
AI	-0.029*** (0.000)	-0.003 (0.447)	-0.025** (0.025)	-0.002** (0.003)	-0.002*** (0.000)	-0.002*** (0.000)	-0.003*** (0.000)	-0.003*** (0.000)	-0.003*** (0.000)	-0.0032*** (0.000)	-0.0033*** (0.000)
NR	0.0872*** (0.000)	0.001 (0.815)	0.084*** (0.000)	0.085*** (0.000)	0.085*** (0.000)	0.0086*** (0.000)	0.087*** (0.000)	0.088*** (0.000)	0.088*** (0.000)	0.088*** (0.000)	0.0898*** (0.000)
RE	-0.052*** (0.000)	0.001 (0.680)	-0.055*** (0.000)	-0.054*** (0.000)	-0.005*** (0.000)	-0.053*** (0.000)	-0.0522*** (0.000)	-0.052*** (0.000)	-0.0516*** (0.000)	-0.0513*** (0.000)	-0.0504*** (0.000)
SI	-0.0199** (0.044)	-0.0004 (0.947)	-0.0192 (0.273)	-0.0195 (0.177)	-0.0196 (0.117)	-0.019* (0.068)	--0.0200** (0.020)	--0.020** (0.017)	-0.020** (0.013)	-0.0203** (0.011)	-0.0205** (0.017)
GF	-2.76e-10*** (0.000)	8.01e-12 (0.831)	-2.89e-10** (0.005)	-2.84e-10** (0.001)	-2.81e-10*** (0.000)	-2.78e-10*** (0.000)	-2.73e-10*** (0.000)	-2.72e-10*** (0.000)	-2.71e-10*** (0.000)	-2.69e-10*** (0.000)	-2.66e-10 *** (0.000)
EG	5.36e-13*** (0.000)	2.05e-14 (0.165)	5.03e-13** (0.000)	5.15e-13*** (0.000)	5.22e-13*** (0.000)	5.30e-13*** (0.000)	5.43e-13*** (0.000)	5.45e-13*** (0.000)	5.49e-13*** (0.000)	5.53e-13*** (0.000)	5.63e-13*** (0.000)
URB	0.0087* (0.082)	0.0002 (0.995)	0.0086 (0.337)	0.008 (0.243)	0.00865 (0.179)	0.00866 (0.119)	0.00867** (0.050)	0.0087** (0.044)	0.0086** (0.037)	0.00868** (0.035)	0.0087** (0.048)

Where ***, **, and * indicate significance at 1, 5 and 10 %, respectively.

Conclusion and Policy Recommendations

Asia, a continent with diverse economic systems and industrial giants, faces environmental problems due to deforestation, air and water pollution, and greenhouse gas emissions. However, it also brings with it advances in technology and higher living standards. The depletion of natural resource stocks is a significant global concern, with humans consuming three times as many resources by 2050. This has led to environmental degradation, particularly in Asia, where emerging nations face challenges such as land development and the management of water, air, and forests. To address this issue, it is crucial to investigate the relationship between reducing energy use and advancing sustainable environmental innovation. Sustainable development requires balancing ecological sustainability, equitable resource distribution, and economic growth. Because of its diverse environments and sizable population, Asia needs specialised strategies for sustainability. In this context, this study examined the effects of carbon finance (CF), artificial intelligence (AI), green energy (GE), total natural resource (TNR), and sustainable innovation (SI) on environmental quality in three Asian countries over the 2000 to 2021 period using the DKSE approach. The results indicate that CF, GE, and AI have a positive relationship, but NR and EG have a negative relationship with EQ.

The study offers policy recommendations to limit resource exploitation and reduce carbon emissions by implementing appropriate plans and environmental levies. Furthermore, governments and financial institutions should focus on sustainable innovation practices and invest in green energy, carbon finance and AI. Asian governments should integrate resource management policies grounded in the sustainable use of natural resources. This can be achieved through establishing regulations to foster responsible extraction and conservation. Governments should also give priority to green energy through regulatory frameworks and sustainable energy programmes. This can also be done through collaboration between the public and private sectors. Governments in Asia can capitalise on the private sector's capabilities and resources to foster green energy projects and implement AI-driven projects. Furthermore, carbon-emission reduction initiatives should be proposed through collaboration between financial institutions and the government.

Theoretical and Practical Implications

This study confirms the factors that contribute to environmental outcomes, thereby extending the existing literature on environmental sustainability. This study has contributed to the existing literature by including AI as a predictor, an emerging factor that has not been extensively explored in the context of the studied economies. The study offers empirical evidence using a robust methodology. In addition, future researchers can utilise the findings of this study to extend the topic across different contexts further. In terms of practicality, the study provides policymakers with insights, shedding light on the role of policy interventions in driving environmental sustainability efforts. Policy measures are needed to promote green practices which reduce carbon emissions, leading to better environmental outcomes in the Asian countries.

Limitations and Future Research Directions

This study offers a significant contribution to the context of Asian economies. Nonetheless, certain restrictions should be considered and utilised by future researchers to expand the current investigation further. Firstly, this study examined different Asian economies, but no individual comparisons between countries were conducted. Consequently, future research can focus on evaluating the association between the model's predictors and environmental quality for each country independently. Additionally, the variables included in the study can be measured using different indicators. For instance, environmental outcomes can be measured using greenhouse gas emissions rather than carbon emissions, as well as the ecological footprint. Moreover, a different sample of countries can be used; for instance, a similar analysis can be conducted by grouping countries by income level or economic bloc. This study employed a specific econometric methodology to provide results. In future investigations, researchers can apply different methodologies. Future research could expand the dataset's time span by including updated data.

Declaration of generative AI and AI-assisted technologies:

The basic and AI features of Grammarly tool have been used to improve the English language of this paper.

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