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The impact of innovation and renewable energy on CO_2 emission in Asian developing countries

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Abstract

This study examines the impact of innovation and renewable energy on CO_2 emissions in a sample of 15 developing Asian countries from 2000 to 2020. Using panel data regression analysis, it identifies two key findings. First, innovation - measured by research and development (R&D) expenditures and the number of patents - leads to an increase in CO_2 emissions, likely driven by the scale effect, whereby economic growth and technological advancements initially result in higher emissions. Second, a higher share of renewable energy consumption significantly reduces emissions, underscoring the critical role of clean energy in mitigating environmental impacts. The findings also support the Environmental Kuznets Curve (EKC) hypothesis, suggesting that as income levels rise, emissions initially grow but eventually decline as economies transition toward greener technologies. Additionally, the study highlights population growth and afforestation as significant factors influencing CO_2 emissions. By offering empirical evidence, this research provides valuable guidance for policymakers in developing Asian nations, emphasizing the need to balance innovation with greater investments in renewable energy to achieve sustainable development and lower carbon emissions.

Keywords: CO_2 emissions, Renewable energy, Innovation

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1. Introduction

With the world facing severe challenges from climate change to the sustainable development of humanity, the need to urgently reduce CO_2 emissions, the primary cause of climate change, becomes increasingly imperative. According to data from the World Bank, Asia has experienced the fastest growth in CO_2 emissions. Countries in the study contributed approximately 48% of the total global CO_2 emissions in 2020. CO_2 emissions in Asian developing countries nearly tripled over 21 years, from 5.7 billion tons in 2000 to 15.9 billion tons in 2020. The early 2000s saw a sharp increase due to the region's accelerated industrialization and urbanization. This necessitates enhanced efforts by Asian countries to minimize CO_2 emissions and address the consequences of climate change.

The slowdown in emissions growth after 2010, particularly the slight dip between 2014 and 2016, could be seen as a positive indication that efforts to manage emissions are beginning to show results. From 2011 to 2020, the total CO_2 emissions increased by only 2.6 billion tons, approximately one-third of the increase observed in the first decade. This aligns with global efforts, policies, and the increasing awareness of environmental issues. However, despite this progress, the overall upward trend in emissions highlights the urgent need for more effective interventions.

Faced with immense challenges in reducing CO_2 emissions in the region, innovation and renewable energy emerge as pivotal factors for addressing climate change-related issues. Between 2000 and 2020, innovation in the studied countries showed significant growth, highlighting the increasing focus on innovation across the region. According to the World Bank data, the total number of patents surged over 45 times, rising from 0.03 million to 1.39 million. Meanwhile, R&D expenditure also saw an upward trend, increasing from an average of 0.36% of GDP to 0.55% in 2020.

Although following a similar upward trend, the rate of emissions increase shows signs of slowing as the number of patents rises, suggesting that innovation may help decelerate emissions growth even as economic activities expand. However, this correlation remains weak. Specifically, in some countries where the number of patents reached 0.7 million, the continued increase in patents only resulted in CO_2 emissions showing minimal reduction, either staying flat or continuing to rise. This suggests that innovation alone may not suffice to curb emissions without complementary measures, such as renewable energy initiatives, to offset the environmental impacts of industrialization. Additionally, the potential for endogeneity between CO_2 emissions and R&D expenditure poses a limitation that could influence the observed relationships, highlighting a need for caution in interpreting the impact of innovation on emissions. Although renewable energy generation has steadily increased over the study period, its total national energy consumption share has declined. This divergence points to a critical issue: despite investments in renewable energy, the region's overall energy demand has continued to grow, and non-renewable energy sources have expanded more rapidly to meet this demand. The decline in renewable energy's share is a significant concern, as it indicates that renewable energy production is not keeping pace with the broader economic expansion. This disparity may be one reason why CO_2 emissions continue to rise despite promising innovation and advancements in renewable energy output.

The practical correlations between innovation, renewable energy, and CO_2 emissions highlight the potential impact of these two factors on the environment. While efforts in research, innovation, and renewable energy in Asia may not yet have led to a significant reduction in annual CO_2 emissions, they have contributed to curbing the rate of environmental pollution and climate change.

Despite the promising trends, previous studies have not fully explored the role of innovation and renewable energy in addressing CO_2 emissions, particularly in the context of Asian developing countries. While it is well known that innovation and renewable energy are critical for tackling climate change, the specific dynamics of how these factors interact within emerging economies in Asia remain understudied. This study aims to fill this research gap by focusing on the dual impact of innovation and renewable energy on CO_2 emissions in these countries, where rapid industrialization and urbanization have contributed significantly to global emissions. By focusing on Asian developing countries, this research addresses a critical regional aspect of climate change that has not been sufficiently highlighted in the literature.

The remainder of the paper is organized as follows. Section 2 provides a literature review and theoretical background. Section 3 outlines the empirical approach and describes the dataset. Section 4 presents and analyzes the empirical results, while section 5 offers policy implications based on the findings. Finally, section 6 concludes the study.

2. Literature review and theoretical background

2.1 Literature review

Numerous previous studies have found evidence indicating that innovation has an impact on reducing CO_2 emissions. Concerning the effect of innovation on carbon emissions, Fang *et al.* (2022) revealed that R&D contributes to carbon emission reduction and achieves green economic recovery, while technology spillovers play a significant role in reducing CO_2 emissions in the South Asian region. Similarly, by investigating the impact of innovation on sustainable growth, Fernández *et al.* (2018) utilized OLS regression for data from 17 developed countries, supporting the hypothesis that R&D expenditure positively contributes to CO_2 emission reduction. Additionally, in the context of ASEAN's focus on increasing R&D expenditure, Mehmood *et al.* (2022) also found similar results regarding the relationship between R&D expenditure and ecological footprint in ASEAN. Investigating the long-term relationship between innovation and CO_2 emissions reduction, Shahbaz *et al.* (2020) conducted a study based on 148 years of historical data from the United Kingdom to examine the existence of a relationship between CO_2 emissions and independent variables. The research findings show that increased R&D expenditure helps reduce CO_2 emissions. Estimated environmental impacts support the Environmental Kuznets Curve (EKC) hypothesis, with a reverse U-shaped relationship between economic growth and R&D expenditure with CO_2 emissions. The results of these studies consistently demonstrate the positive impact of innovation on reducing CO_2 emissions; however, the extent of this impact varies.

Additionally, some studies have indicated that the impact of innovation is not uniform within the same model due to variations in research methods, differences in average income levels, or the unique characteristics of individual countries. Using multiple estimation methods, Qi *et al.* (2022) investigated the impact of urbanization, R&D expenditure, infrastructure development, and real income on CO_2 emissions in Asian countries. According to the estimation results using MG, FMOLS, and DOLS, R&D expenditure has a significantly positive impact on CO_2 emissions, while the DK estimation tool indicates a non-significant impact. Sakariyahu *et al.* (2023) found that innovation and economic freedom significantly improve environmental quality in low-middle and upper-middle income African countries, while the opposite effect was observed in low-income countries, where innovation tends to exacerbate environmental degradation. Petrović and Lobanov (2020) analyzed the impact of research and development (R&D) expenditure on CO_2 emissions in 16 countries within the Organization for Economic Co-operation and Development (OECD) from 1981 to 2014. While their short-term regression model indicates that, on average, R&D does not contribute to reducing CO_2 emissions for most countries studied, in the long run, it shows a positive environmental effect.

The impact of renewable energy on CO_2 emissions has also been a key area of research. Jebli *et al.* (2020) explored the relationship between renewable energy consumption, CO_2 emissions, and value-added across different income levels. They found that renewable energy consumption reduces CO_2 emissions, with the most substantial impact occurring in low-income countries. Mita *et al.* (2017) conducted a robust analysis of the role of renewable energy and institutions in economic growth and reducing CO_2 emissions, concluding that both factors are crucial in fostering sustainable development, with institutional support needed to expand renewable energy use across sectors. Alongside its positive momentum, the environmental impact of green energy becomes clearer when analyzed from two perspectives: the level of consumption and the efficiency of energy use. Altin *et al.* (2024) investigated the effects of two aforementioned aspects on carbon emissions in G7 countries, finding a long-run cointegration relationship between the variables. Their results show that while increased energy efficiency reduces carbon emissions, a positive correlation exists between renewable energy consumption and emissions.

Not only do they have individual effects, but numerous studies have also indicated that renewable energy and innovation simultaneously impact CO_2 emissions. Usman and Balsalobre-Lorente (2022) identified the co-directional impact of economic growth and coal energy consumption, contrary to the impact of thermal consumption, economic complexity, and innovation on the ecological footprint in newly industrialized countries during the period 1990-2018. For the specific case of Indonesia, Asif *et al.* (2023) indicated that the increase in renewable energy, technological innovation, and forests contributes to an improvement in the environment, while economic growth leads to environmental degradation. In addition to direct effects, some studies have indicated that innovation also moderates CO_2 emissions through renewable energy. Cheng *et al.* (2021) investigated the effects of innovation on CO_2 emissions for 35 OECD countries, finding that innovation directly reduces CO_2 emissions and moderates them through economic growth and renewable energy; however, this impact is not uniform across countries. Churchill *et al.* (2019) examined the impact of R&D on CO_2 emissions in G7 countries, discovering the potential for both positive and negative effects due to simultaneous influences of GDP and energy efficiency in production.

Governments worldwide emphasize the importance of innovation and renewable energy in reducing CO_2 emissions. However, while many studies have focused on either innovation or renewable energy's impact on emissions, few have simultaneously explored these factors in the context of developing countries, particularly in Asia, where rapid industrialization poses unique challenges. This study makes an empirical contribution by investigating the dual impact of innovation and renewable energy on CO_2 emissions in Asian developing countries in the scenario of the non-linear effect of income per person on the environment according to the EKC hypothesis, offering new insights into how these factors interact within the context of emerging economies.

2.2 Theoretical background

Environmental Kuznets Curve (EKC) is an important economic hypothesis addressing the impact of innovation on environmental quality through the influence of economic growth, as illustrated in Figure 1.

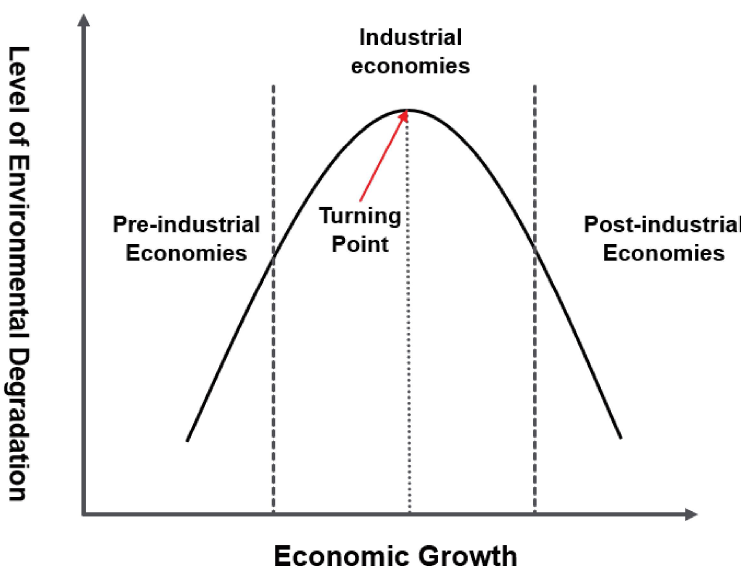

Figure 1. Environmental Kuznets Curve

Source: Authors' compilation based on the EKC hypothesis

Galeotti and Lanza (2005) explained this relationship based on the application of technological advancements in production. In the pre-development stage, growth accompanied by innovation requires significant resource inputs, leading to increased resource exploitation and, consequently, higher CO_2 emissions into the environment. However, as the economy transitions beyond a certain threshold, innovative technologies become capable of reducing CO_2 emissions by improving resource efficiency, developing renewable energy, processing and recycling emissions, etc. With higher income levels, countries can invest more in innovative technologies, thereby replacing polluting technologies with environmentally friendly ones or even technologies that improve environmental quality. Therefore, the following hypothesis is suggested:

H1: The economy's scale impacts CO_2 emissions as per the EKC model.

Despite ongoing debates and limitations, EKC remains an important hypothesis concerning environmental factors. Innovation is considered a decisive factor in improving the environment in the post-development stage of the economy (Galeotti and Lanza, 2005).

Alongside criticism of the limitations of the EKC hypothesis, some researchers have advocated for adding explanatory variables for environmental pollution, among which the STIRPAT model has received considerable support. This is a stochastic regression model developed from the IPAT equation, where Population (P), Affluence (A), and Technology (T) are considered the three main factors impacting the environment (Environmental Impact (I)). Innovation at different times and to varying degrees throughout history has demonstrated both positive and negative impacts on the environment through its influence on other factors (Chertow, 2000; Alcott, 2010). Although many theoretical foundations and studies imply that innovation improves the environment, its impact remains uncertain due to its varied effects across different contexts. Therefore, the following hypothesis is developed:

H2: Innovation has an impact on CO_2 emissions.

Renewable energy is considered a crucial solution for reducing CO_2 emissions as it addresses the primary source of emissions: the production and use of fossil fuels. Research by Amin *et al.* (2023) has shown that adopting renewable or clean energy and significant government efforts to mitigate the adverse effects of climate change will undoubtedly promote sustainable development and a cleaner environment worldwide. Therefore, the following hypothesis is suggested:

H3: The increase in the proportion of renewable energy usage will reduce CO_2 emissions.

The STIRPAT model also indicates that population is one of the three main factors influencing the environment, exerting pressure on the environmental system. Additionally, according to Malthus' theory of population growth (1798), the population tends to increase exponentially if the birth rate is not controlled, exceeding resource provision capacity and leading to ecological disasters. This hypothesis has faced criticism for not accounting for the impact of technological development, institutions, and trade, but it has also become the foundation for many subsequent studies (Sherbinin *et al.*, 2007). Therefore, the following hypothesis is developed:

H4: The growth of the population will increase CO_2 emissions.

Forests are one of the leading natural factors that help balance CO_2 in the atmosphere. Forests act as carbon sinks, absorbing CO_2 from the atmosphere through photosynthesis and storing carbon in trees and vegetation. This process plays a crucial role in mitigating the greenhouse effect by reducing the amount of CO_2, one of the primary greenhouse gases responsible for global warming. However, human activities, such as deforestation and land-use change, disrupt this natural balance by reducing forest cover, leading to increased CO_2 levels as less carbon is absorbed and more CO_2 is released through activities like logging and land clearing. Most previous studies have supported the notion that forests negatively correlate with emissions. Rawshan *et al.* (2020) and Asif *et al.* (2023) indicated that the decline of forested areas impacts the rise in CO_2 emissions. Therefore, the following hypothesis is suggested:

H5: The increase in the proportion of forest area will reduce CO_2 emissions.

3. Research methods

3.1 Model

Based on the theoretical foundation of the EKC, the STIRPAT model, and previous studies by Rawshan *et al.* (2020), Qi *et al.* (2022), and Cheng *et al.* (2021), we propose to construct a quantitative model as follows:

$$lnCO_{2i,t} = \beta_0 + \beta_1 \times lnGDP_{i,t} + \beta_2 \times lnGDP_{i,t}^{\,2} + \beta_3 \times lnRD_{i,t} + \beta_4 \times lnPat_{i,t} +$$
$$\beta_5 \times lnRen_{i,t} + \beta_6 \times lnPop_{i,t} + \beta_7 \times Forest_{i,t} + u_{i,t},$$

where β_0 is intercept coefficient; β_j are slope coefficients ($j = \overline{1, 7}$); $u_{i,t}$ is random effect of country i in year t; $CO_{2i,t}$ represents CO_2 emissions of country i in year t (kiloton); $GDP_{i,t}$ stands for GDP per capita at purchase power parity of country i in year t (\$); $RD_{i,t}$ denotes R&D expenditure as a percentage of GDP of country i in year t (%); $Pat_{i,t}$ represents the number of patents of country i in year t; $Ren_{i,t}$ stands for renewable energy consumption share of country i in year t (%); $Pop_{i,t}$ represents the population of country i in year t (people); and $Forest_{i,t}$ denotes forest area as a percentage of land area of country i in year t (%).

3.2 Data

The data used as a research sample is panel data from 15 developing countries (see Appendix A) in Asia over 21 years, from 2000 to 2020. This period was selected to capture the region's most recent two decades of rapid economic growth and industrialization, which coincide with significant increases in CO_2 emissions, making it a relevant timeframe for examining the relationship between economic growth and environmental impact. According to the Australian government's list of developing countries (Australian Department of Foreign Affairs and Trade, 2022), there are 25 Asian countries classified as developing. However, some countries on this list had insufficient data for the 2000-2020 period. Therefore, 15 countries with complete datasets were selected. These countries also represent the largest economies among the 25 developing nations, making them suitable for reflecting the challenges developing countries face in balancing economic growth with environmental sustainability. The data for all variables were collected from the World Bank.

Table 1. Summary of variables, data sources, and research hypotheses

Variable	Variable symbol	Measurement unit	Expected impact	Theoretical background
CO_2 emissions	CO_2	Kiloton		
Economy's scale	GDP	USD (GDP per capita, PPP)	+/-	EKC, STIRPAT
Innovation	RD	% of GDP	+/-	STIRPAT, Sakariyahu *et al.* (2023), Henriques and Borowiecki (2017)
	Pat	Number of patent applications		
Renewable energy	Ren	% of energy consumption	-	Amin *et al.* (2023), Cheng *et al.* (2021)
Population	Pop	Number of persons	+	Malthus (1798), STIRPAT, Qi *et al.* (2022)
Forest area	Forest	% of land area	-	Rawshan *et al.* (2020), Asif *et al.* (2023)

Source: Authors' compilation

3.3 Statistical description and correlation matrix

Table 2 presents the findings of the summary measurements among variables.

Table 2. Summary statistics of variables

Variables	Observation	Mean	Standard deviation	Min	Max
CO_2	315	772548.1	2036261	2133.81	1.09E+07
GDP	315	8936.731	6290.392	1037.941	30164.6
RD	315	0.423	0.450	0.039	2.406
Pat	315	37047.84	184114	0	1393815
Ren	315	25.18	19.84	0.44	64.58
Pop	315	2.30E+08	4.23E+08	2450979	1.41E+09
Forest	315	22.240	18.385	1.141	59.934

Source: Authors' calculation

The average CO_2 emissions in the studied countries are approximately 772.5 million tons per year. China consistently has the highest annual CO_2 emissions in Asia, with the highest value exceeding 10 billion tons in 2020. The lowest CO_2 emissions were recorded in Tajikistan at just over 2 million tons in 2002.

The average GDP per capita is 8.93 thousand USD. Kazakhstan had the highest GDP per capita, reaching 30.16 thousand USD in 2020, while Tajikistan had just over 1000 USD in 2000.

The average expenditure on R&D as a percentage of GDP is 0.42%. Indonesia had the lowest R&D expenditure as a percentage of GDP, at 0.039% in 2003. On the other hand, China had the highest R&D expenditure as a percentage of GDP, exceeding 2.4% in 2020.

On average, each country had over 37 thousand patents per year. China reached 1.4 million new patents in 2018, while Tajikistan had not recorded any new patents for several years.

Asia's average renewable energy usage rate is 25.2%, higher than the world average of 17.34%. Despite the high proportion of renewable energy, this index's development trend is contrary to the global trend, with most countries experiencing a gradual decline in their share of green energy over the years.

Most Asian countries have large populations, with an average of 158 million people per country. China leads the region and the world with over 1.41 billion people in 2020. Mongolia has the lowest population, with 2.45 million people in 2000.

The average forest area is 22.24%. Malaysia had the highest proportion of the industrial sector in the region, reaching 59.93% in 2000. In contrast, Kazakhstan had the lowest proportion, at 1.14% in 2010.

Overall, there is a significant disparity among the studied countries due to differences in technological advancement and economic growth rates. The descriptive statistical results do not strongly indicate the positive impact of innovation and renewable energy on reducing emissions.

Table 3. Correlation description

	$lnCO_2$	**lnGDP**	**$lnGDP^2$**	**lnRD**	**lnPat**	**lnRen**	**Forest**	**lnPop**
$lnCO_2$	1.00							
lnGDP	0.39	1.00						
$lnGDP^2$	0.38	0.99	1.00					
lnRD	0.64	0.27	0.27	1.00				
lnPat	0.87	0.42	0.42	0.70	1.00			
lnRen	-0.18	-0.53	-0.54	-0.17	-0.26	1.00		
lnPop	0.87	0.02	0.01	0.50	0.67	0.27	1.00	
Forest	0.10	-0.05	-0.07	-0.11	-0.09	0.18	0.20	1.00

Source: Authors' calculation

Table 3 shows that the correlation coefficients between the independent variables lnGDP, $lnGDP^2$, lnRD, lnPat, lnPop, Forest, and the dependent variable $lnCO_2$ are positive, indicating a positive relationship with CO_2 emissions. The correlation coefficient between the variable lnRen, and the dependent variable $lnCO_2$ is negative, indicating a negative relationship with CO_2 emissions. Regarding the correlation between the independent variables, all variables exhibit moderate correlations except for lnGDP and $lnGDP^2$. This increases the likelihood of multicollinearity issues in the model; however, combining these two variables is necessary to test the EKC hypothesis.

4. Results and discussion

4.1 Results

After performing descriptive statistics and examining the correlation matrix between variables, we proceeded to estimate and test the model using three methods: ordinary least squares (OLS), random effects (RE), and fixed effects (FE). The Breusch-Pagan Lagrange multiplier test yielded a p-value of 0.00 and lower than 0.05, indicating that the OLS model is inappropriate. Thus, the RE model was chosen. Next, the Hausman test was conducted to select between SE and RE. The result obtained p-value is 0.36 and lower than 0.05, suggesting the presence of fixed effects at the 5% significance level, making the RE model the best choice. Subsequently, diagnostic tests were performed to examine the regression model's assumptions, thereby addressing and improving its reliability.

Heteroskedasticity test. The Breusch-Pagan Lagrange multiplier test yielded a p-value lower than 0.05, indicating that the model suffers from heteroskedasticity.

Autocorrelation test. The Wooldridge test for autocorrelation resulted in a p-value of 0.000 and lower than 0.05, indicating that the model suffers from autocorrelation.

Multicollinearity test. The mean variance inflation factor (VIF) was 168.13 and greater than 10, indicating multicollinearity in the model.

Thus, the diagnostic tests indicate that the model suffers from multicollinearity, heteroskedasticity, and autocorrelation. To address these issues, robust standard errors were employed to mitigate the impact of these phenomena. The results of the model are presented in Table 4.

Table 4. Results

Independent Variables	(POLS)	(RE)	(FE)	(RE robust)
lnGDP	1.505**	1.805***	1.881***	1.805***
	(0.603)	(0.326)	(0.331)	(0.391)
$lnGDP^2$	-0.061*	-0.083***	-0.085***	-0.083***
	(0.034)	(0.018)	(0.018)	(0.020)
lnRD	0.086***	0.023	0.023	0.023
	(0.028)	(0.016)	(0.016)	(0.030)
lnPat	0.156***	0.066***	0.063***	0.066**
	(0.016)	(0.011)	(0.011)	(0.028)
lnRen	-0.348***	-0.364***	-0.340***	-0.364***
	(0.017)	(0.032)	(0.035)	(0.111)

Table 4. Results *(continued)*

Independent Variables	(POLS)	(RE)	(FE)	(RE robust)
lnPop	0.871***	0.955***	0.803***	0.955***
	(0.019)	(0.056)	(0.144)	(0.088)
Forest	0.001	-0.002***	-0.002***	-0.002**
	(0.001)	(0.000)	(0.000)	(0.001)
Constant	-12.29***	-14.08***	-11.90***	-14.08***
	(2.591)	(1.614)	(2.571)	(2.394)
Observation	309	309	309	309
R-squared	0.974		0.81	
Country		15	15	15

Notes: Standard errors are in parentheses. *, **, and *** indicate statistical significance at 10%, 5%, and 1%, respectively.

Source: Authors' calculation

4.2 Results discussion

The estimation results indicate a U-shaped relationship between GDP and CO_2 as per the EKC hypothesis in Asian developing countries. At a significance level of 1%, the coefficient of lnGDP is positive and $lnGDP^2$ is negative, suggesting a reverse U-shaped relationship between GDP and CO_2 emissions. This result reaffirms the existence of the EKC hypothesis (hypothesis 1), similar to the findings of Mehmood *et al.* (2022), especially within the scope of Asian countries. The turning point of the model is at lnGDP = 10.8, corresponding to the GDP of $e^{10.8}$ = 49,020 USD per capita per year. This turning point is more than four times higher than the average of studied countries in 2020 (13,126 USD per capita per year), indicating a major gap between current economic levels and the threshold where environmental improvements might begin. It highlights the need for policies that promote economic development while actively investing in green technologies and renewable energy sources, ensuring that environmental improvements can be achieved before such high-income levels are reached. It also suggests that without targeted interventions, environmental degradation may continue for a long time before the benefits of economic growth lead to lower emissions.

Regarding innovation, the estimation results show that R&D expenditure does not yet have a statistically significant impact on environmental improvement. This may be due to several factors specific to Asian developing countries. The focus of R&D investment might not be directed toward green technologies or environmental sustainability. Instead, these expenditures could be allocated to industries prioritizing short-term economic growth over long-term environmental goals. Additionally, the impact of R&D on CO_2 emissions might take longer to manifest, as green technologies typically have longer development and adoption cycles. Therefore, this finding suggests a need for future research to investigate how R&D

can be more effectively aligned with sustainability objectives and how policy frameworks can support the faster adoption of green technologies.

On the other hand, the number of patents does show a statistically significant positive relationship with CO_2 emissions at the 5% level, indicating that a 1% increase in the number of patents leads to a 0.066% increase in emissions. The regression model results confirm hypothesis 2 that innovation affects CO_2 emissions, supporting the findings of Sakariyahu *et al.* (2023) but contradicting the studies of Henriques and Borowiecki (2017) and Dong *et al.* (2022). This outcome can be explained by the fact that the innovation process necessitates higher production-related resource consumption and CO_2 emissions (the "scale effect") while simultaneously having the ability to boost production efficiency and lower emissions per unit of output (the "efficiency effect"). However, the association between CO_2 emissions and innovation suggests that, given the existing level of invention in these countries, the degree of innovation is still insufficient to successfully overcome the scale effect, leading to unfavorable results. In the specific context of Asian developing countries, this phenomenon can be attributed to several factors, including limited access to advanced technologies, insufficient infrastructure to support sustainable practices, and reliance on resource-intensive industries that exacerbate emissions despite innovation efforts.

The coefficient for the share of renewable energy usage is negative, indicating a reverse relationship of this index to CO_2 emissions at a significance level of 1%. This index yields the most positive result for the environment, as a 1% increase in the use of renewable energy leads to 0.364% decrease in CO_2 emissions, ceteris paribus. This aligns with the studies of Cheng *et al.* (2021) and supports hypothesis 3 regarding the relationship between renewable energy and CO_2 emissions. However, in emerging economies, the transition is characterized by a shift from reliance on widely adopted clean energy sources, such as hydropower, to a growing dependence on fossil fuels. With the current technological and economic capabilities of these countries, more efficient renewable energy sources like solar and biomass are still in the research phase and have not yet been widely implemented. This shift highlights the challenges these nations face in balancing immediate energy needs with sustainable practices, ultimately impacting their overall emissions.

The coefficient of 0.955 for the population indicates a positive impact of this indicator on CO_2 emissions at the 1% significance level. With the same level of other factors, countries with higher populations tend to have additional increases in CO_2 emissions. This result is also found in the study by Qi *et al.* (2022) and confirms hypothesis 4 regarding the impact of population on CO_2 emissions. This is consistent with theoretical foundations and the research hypothesis, as population growth directly affects energy demand and CO_2 emissions.

Forest area also shows a positive impact on the environment with a negative coefficient at a significant level of 5%. Thus, ceteris paribus, a 1% increase in the forest area (% of land area) leads to a 0.002% decrease in CO_2 emissions. This aligned with the studies of Rawshan *et al.* (2020) and supports hypothesis 5 regarding the relationship between forest area and CO_2 emissions. This relationship suggests more than just the intuitive role of forests as natural carbon sinks. The findings also reflect the impact of deforestation and reforestation trends in Asian developing countries, where forest management policies play a crucial role.

Thus, innovation has not directly shown a positive impact on reducing CO_2 emissions in Asian developing countries, while renewable energy has yielded positive results. Therefore, promoting renewable energy usage can be a key solution for countries to focus on addressing environmental issues more effectively.

The regression model results show statistically significant impacts on CO_2 emissions from several factors, including those that reduce emissions and others that increase them. Specifically, renewable energy consumption and forest area have negative effects, while economic and population growth have positive effects. Notably, GDP per capita shows a nonlinear relationship with CO_2 emissions, with a turning point significantly higher than the current GDP levels in developing countries. This will serve as the foundation for the study to propose solutions to reduce emissions in the region, particularly emphasizing innovation in the renewable energy sector.

5. Policy implications

The research findings indicate that the GDP per capita turning point is significantly higher than the current level, while economic development remains a top priority for most countries. Even though traditional innovation indicated through a number of patents also promotes the CO_2 emissions due to the prevalence of scale effect over efficiency effect. As a result, the negative environmental impacts of growth are inevitable. However, based on the model results, the negative consequences can be mitigated by focusing on other influencing factors, such as promoting renewable energy use and innovative development in the renewable energy sector, reducing population growth, and expanding forested areas.

5.1 Promoting innovation in renewable energy

Innovation in renewable energy plays a crucial role in reducing CO_2 emissions in Asian developing countries. By increasing investment in green R&D, countries can develop technologies that reduce emissions across various sectors, such as energy, manufacturing, and transportation. To lower CO_2 emissions, nations need to focus on innovation projects that are environmentally focused, promote and support research that directly contributes to emission reduction. Renewable energy is a critical, innovative solution, and countries must transition away from fossil fuels by actively investing in clean energy technologies.

Firstly, governments should prioritize policies that encourage innovation in renewable energy, such as streamlining administrative processes, reducing investment risks, and creating incentives to attract private sector investments. Simplifying bureaucratic hurdles and accelerating approval processes for renewable energy projects can make investments more attractive to both local and international investors.

Secondly, industrial protection can be offered to support renewable energy enterprises, helping them mitigate financial burdens and improve competitiveness in domestic and international markets. Tax credits, grants, or low-interest loans should be provided to businesses and startups innovating in renewable energy, particularly in areas such as solar, wind, and bioenergy. This will boost innovation and make renewable energy solutions more competitive compared to fossil fuels. Innovation investment should be selective to avoid inefficient innovations that may inadvertently increase emissions.

Furthermore, regional cooperation is essential for transferring knowledge and best practices between countries. Collaborative frameworks for technology transfer and shared research platforms will ensure that even countries with limited resources can benefit from the latest advancements in green energy. Developing countries should focus on scaling technologies suitable for their specific energy needs and economic conditions, such as small-scale solar or biomass solutions.

5.2 Other policies

In addition to innovation, economic growth, population, and forest area, which have been identified as factors impacting CO_2 emissions, countries in the region need to develop appropriate policies to address their impacts on the environment.

Population control policies need to be tailored to each country based on its population situation and economic development level. Given the potential trend of population aging and the continued pursuit of economic growth, in addition to population policies, there should be a strong focus on improving the quality of the workforce, particularly in the renewable energy sector. It is also necessary to raise public awareness through community education on energy-saving measures, renewable energy use, and waste reduction.

Given forests' critical role in maintaining ecological balance, particularly in mitigating CO_2 emissions, the relationship between forest area and emissions highlights the importance of effective forest management policies. Deforestation remains a significant challenge in many Asian developing countries due to factors such as illegal logging, agricultural expansion, and industrial development. These activities contribute to higher CO_2 emissions, undermining environmental goals. In response, countries should enhance their efforts toward implementing stricter deforestation controls and promoting reforestation and afforestation initiatives. Moreover, reforestation efforts and the restoration of degraded lands should be seen as vital strategies to offset the CO_2 emissions produced by industrial activities, helping countries meet their emission reduction targets.

6. Conclusions

Using panel data from 15 developing countries in Asia for the period from 2000 to 2020, this study examines the potential to mitigate CO_2 emissions of several factors such as economic development, renewable energy usage, innovation. This potential is assessed based on the amount of carbon dioxide emissions that can be reduced. The robust RE estimation is determined to be the most appropriate after all robustness checks. Empirical evidence shows that while the renewable energy variable has been demonstrated to have an impact on reducing CO_2 emissions, innovation has not had a favorable environmental impact. The study also discovered that whereas forest areas have an impact on reducing emissions, the population has the opposite impact. The model also confirmed the inverted U-shaped relationship between economic growth and emissions. Consequently, the GDP per capita at purchasing power parity of 49,020 USD is estimated to represent the turning point for these countries, a figure that is now unattainable for most nations. Since most countries in the study sample have incomes below 49,020 USD and are developing nations, growth-led increasing CO_2 emissions are inevitable. Therefore, to mitigate the increase in CO_2 emissions resulting from economic development, nations must focus on creating environmentally friendly innovations, investing in renewable energy, and reducing the share of non-renewable energy, accompanied by implementing population control policies and expanding reforestation efforts to lessen the unavoidable negative environmental impact of economic growth.

There is ongoing debate regarding the use of R&D expenditure and patents as proxies for innovation is incomplete, as they do not account for innovation efficiency. Additionally, the potential endogeneity between CO_2 emissions and R&D expenditure raises concerns, as it could bias the observed relationship between innovation and emissions. Future studies could address this issue by applying econometric techniques to control for endogeneity and adopting new metrics that reflect both the quantity and quality of innovation. Incorporating updated data, especially post-COVID-19, could also help achieve more comprehensive and practical outcomes.

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Appendix A. List of Asian developing countries studied

No.	Country	No.	Country
1	China	9	Pakistan
2	India	10	Philippines
3	Indonesia	11	Sri Lanka
4	Iran, Islamic Rep	12	Tajikistan
5	Kazakhstan	13	Thailand
6	Kyrgyz Republic	14	Uzbekistan
7	Malaysia	15	Vietnam
8	Mongolia		

Source: Authors' compilation based on the Australian Department of Foreign Affairs and Trade (2022)