RESEARCH ARTICLE

Carbon, Capital, and the Climate: The Economic Puzzle of CO_2 Emissions in South Asia

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Abstract

The rapid rise in carbon dioxide (CO_2) emissions is a major contributor to global warming, making it crucial to understand the key drivers, especially in vulnerable regions like South Asia. This study analyzes the determinants of CO_2 emissions in South Asia from 2000 to 2021 using Environmental Kuznets Curve (EKC) modeling, multiple linear regression, and panel data analysis. Findings indicate that GDP per capita is a primary driver of emissions, while renewable energy helps mitigate carbon emissions. However, the EKC model does not confirm an inverted U-shaped relationship, suggesting South Asia has yet to reach the turning point where economic growth curbs emissions. The findings also suggest that urbanization, industrialization, and per capita energy use contribute to emissions. Panel data analysis, incorporating the Paris Agreement as a structural break, reveals its limited impact on reducing emissions in the region, stressing the need for stronger policy enforcement. The study underscores the importance of accelerating renewable energy adoption, promoting sustainable urbanization, and decarbonizing industries to address climate challenges. Policymakers need to enhance regional cooperation and integrate low-carbon strategies to achieve sustainable development while combating climate change in South Asia.

Keywords: Environmental Kuznets Curve; CO_2 Emissions; South Asia; Renewable Energy; Paris Agreement

Introduction

The relationship between economic development and environmental deterioration has been a crucial area of research in environmental economics. The role of economic factors in determining carbon emissions remains an important issue for countries undergoing rapid industrialization and urbanization (Li and Lin, 2015). South Asia is a prime example in this regard. The region has a unique combination of developing economies, diverse energy portfolios and high population density (Fang, Liu and Putra, 2022), which makes it a pivotal case for examining the determinants of carbon emissions and their effects on sustainable economic growth. South Asia is one of the world's most vulnerable regions to the impacts of climate change. Increased frequency of severe weather events along with rising temperatures and erratic rainfall patterns in the region have profound implications for the livelihoods and food security (Caesar and Janes, 2018; Khalid and Ahmad, 2021). Rising sea-level further threatens densely populated coastal areas (Sivakumar and Stefanski, 2011). These vulnerabilities underscore the urgency of striving for robust climate policies aimed at climate change mitigation and adaptation to minimize the repercussions of the climate-induced disruptions. Despite these vulnerabilities, South Asia's share in the global greenhouse gases (GHGs) emissions remains uneven. India is the largest economy in the region and accounts for about 7% of the global emissions. However, its per capita emissions are considerably lower than those of developed economies (International Energy Agency (IEA), 2022). The contribution of other countries in the region, such as Pakistan, Bangladesh and Nepal, are far lower and Bhutan has achieved carbon neutrality (Yangka, Rauland and Newman, 2023). The region's progress in fulfilling the commitments under the Paris Agreement is yet to be explored. However, greater ambition is required to enhance its leadership in efforts directed at global emission reduction (Fulton et al., 2017). Economic growth fueled by industrialization in South Asia has considerably contributed to rising CO2 emissions, with key sectors such as energy production and manufacturing playing a dominant role. Islam, Raihan and Islam (2024) report that the brick manufacturing industry in Bangladesh, India and Nepal has expanded significantly in recent years, which has resulted in severe environmental degradation on account of either lack of regulations or weak compliance to the existing laws.

A key demographic trend in South Asia is urbanization (Das and Paul, 2021), which further complicates the situation because it not only drives energy demand but also exacerbates environmental degradation. Rampant urbanization poses challenges concerning waste management along with other issues, which exacerbates environmental degradation (Kaur and Punera, 2023). The region's renewable energy demand remains mostly untapped despite considerable strides in recent years (Asif, Khan, Pandey, 2024). Moreover, industrialization driven economic growth is on the rise in the region, which is generally associated with a rise in carbon emissions, while clean energy adoption along with improvements in energy efficiency are termed as effective mitigation strategies (Stern, 2004). The integration of these variables may provide a comprehensive analysis of the interactions of economic and energy factors with carbon emissions in the region. For instance, Pakistan aims to generate 60% of its energy requirement from renewable resources by 2030 in comparison to the 32% (7% solar and wind and 25% hydro) share at present (International Trade Administration, 2024). Moreover, renewable energy accounts for 40% of India's total capacity and aims to achieve the target of 500 GW of renewable energy production by 2030 (IEA, 2024). However, progress towards achieving ambitious renewable energy production goals varies across the region, which necessitates coordinated efforts to enhance investments in clean energy technologies and infrastructure.

This study examines the determinants of CO_2 emissions per capita in South Asia during the period 2000-2021, with a focus on key drivers like GDP per capita, renewable energy consumption, urban population, energy use per capita and industry value added to GDP. Such relationships have rarely been explored in the context of South Asia. The study is a valuable addition to the growing body of knowledge regarding the impact of economic activities and energy usage on climate change in the developing countries. This paper provides empirical evidence to inform policy decisions in South Asia by examining the relationships between economic and energy variables and their impact on CO_2 emissions per capita. The findings of this study highlight the need for holistic strategies aimed at balancing growth with environmental sustainability. Such strategies are crucial for mitigating climate risks and position South Asia as a proactive participant in the global transition to a low-carbon economy.

This paper is structured as follows: the introduction is followed by a comprehensive literature review, discussing the theoretical framework and key economic and energy variables in light of existing literature. It is followed by methodology, explaining the empirical methods employed in the analysis. Results and discussion section encompass data analysis through econometric models and a detailed discussion of the results. The last part of the study provides a conclusion, summarizing the findings of the study along with policy recommendations.

Literature Review

The relationship between economic growth and environmental degradation has been studied extensively in the environmental economics literature. Theoretical and empirical research aim to examine the dynamics between economic operations and carbon emissions, provide insights into ways through which sustainable development can be achieved. The EKC hypothesis is an influential framework in this discourse. It provides a far-reaching perspective on how economic development impacts environmental outcomes.

Environmental Kuznets Curve (EKC)

The EKC hypothesis suggests an inverted U-shaped relationship between economic growth and environmental deterioration (Grossman and Krueger, 1995). It posits that the early stages of economic development are characterized by rapid industrialization and urbanization, leading to a rise in pollution levels on account of increased fossil fuel consumption and resource exploitation. However, when per capita income increases beyond a certain threshold, the demand for technological advancements, cleaner environmental and strict regulations result in a reduction in pollution levels. The turning point occurs when societies have the political will and resources to prioritize environmental sustainability (Dinda, 2005). Empirical studies provide mixed evidence regarding the validity of the EKC. Stern (2004) argues that the EKC's applicability varies depending on the economic structure of a country, the time period and the type of pollutant. Dinda (2005) stipulates that although several developed countries exhibit the EKC pattern, its relevance for the developing world remains debatable. In South Asia, rising GDP per capita, particularly in India, has led to considerable increase in carbon emission on account of industrial growth and heavy reliance on coal (Sharma and Mehrotra, 2020). While countries like Pakistan and Bangladesh have lower emission levels, their upward economic trajectories may result in similar challenges. Policies aimed at renewable energy adoption along with energy efficiency are crucial for shifting these economies toward the downward slope of the EKC (Rahman and Velayutham, 2020). Environmental degradation is caused by several economic and energy related factors in the post-industrial world (Gorova et al., 2012). Some of these key factors and their relation with CO_2 emissions are discussed here in light of existing literature.

Economic Growth and CO_2 Emissions

Economic development is one of the most important drivers of CO_2 emission around the world. Economic growth, as a result of industrial production, energy consumption and transportation, result in higher emissions (Duan et al., 2022). The positive relationship between economic growth and carbon emissions is well-documented in the economic literature. For instance, Onofrei, Vatamanu and Cigu (2022) examine the relationship between economic growth and CO_2 emissions in the EU and find that the two variables have a cointegrating relationship. Similarly, Ang (2007) concludes that GDP per capita has a strong positive relationship with carbon emissions in France. The study highlights the importance of technological and regulatory interventions in mitigating environmental deterioration. Chang and Lee (2014) also show a long-term correlation between GDP per capita growth and carbon emission in industrialized countries. Some studies show that when income levels reach beyond a certain threshold, countries may experience a reduction in carbon emission, as highlighted by the EKC hypothesis. However, the declension point varies among countries depending on factors like regulatory strength, energy mix and technological advancement (Stern, 2004). It implies that economic growth may not ensure environmental improvements in isolation. Deliberate policy measures promoting energy efficiency and clean energy are necessary in this regard (Lu et al., 2020).

In addition to the developed countries, environmental protection has come to the forefront of contemporary issues for developing countries in the recent past due to concerns about the after effects of climate change (Uddin et al., 2017). South Asia is no exception in this regard. The region's economic landscape is characterized by rapid economic growth over the last few decades, particularly in India, Bangladesh and Pakistan. However, such growth has come at a considerable environmental cost. GDP per capita has increased significantly in India alongside a consistent rise in carbon emissions on account of industrialization and heavy reliance on fossil fuels (Tiwari, 2011). Alam et al. (2012) argue that the relationship between GDP growth and carbon emissions is positive in South Asia, as emission increases with an increase in income. They argue that it indicates the early stage of the EKC pattern. Industrialization of the region's certain economies reinforces this trend, driven by urbanization and energy-intensive production (Rahman and Velayutham, 2020). Pakistan's emission trajectory follows a similar economic growth-carbon emissions link, with an immediate need for cleaner energy technologies and effective environmental regulations (Mirza and Kanwal, 2017). It shows that GDP growth continues to be tightly linked with fossil fuel consumption in the entire region, which highlights the absence of widespread adoption of sustainable industrial practices and renewable energy. The region's heavy reliance on oil and coal for energy production amplifies the environmental impact of economic expansion. A decoupling of economic growth and emissions remains elusive in South Asia. It is in contrast to the developed regions, where effective regulations and technological innovations mitigate carbon emissions relative to economic growth (Huisingh et al., 2015). Economic development strategies need to be integrated with carbon reduction mechanisms to prevent locking in high-emissions growth pathways (Bhattacharya et al., 2016).

Renewable Energy Consumption and CO_2 Emissions

The relationship between renewable energy consumption and carbon emissions has gained increasing attention as countries continue their efforts to mitigate climate change. Renewable energy sources like solar, wind, and hydropower are influential in contributing to lower GHG emissions. These are regarded as cleaner alternatives to fossil fuels (Dincer and Acar, 2015). Evidence concerning the negative relationship between renewable energy consumption and CO_2 emission exists in literature. For instance, Al-Mulali, Ozturk and Lean (2015) report that a rise in renewable energy use tends to reduce CO_2 emission in both developed and developing countries. Similarly, Namahoro et al. (2021) argue that in developing countries, an increase in the share of renewables in total energy consumption leads to a reduction in carbon intensity. It is important to mention that the extent to which renewable energy reduces carbon emissions depends on several factors, including policy frameworks (Agupugo et al., 2022), technology adoption rates and energy infrastructure (Usman and Radulescu, 2022). Bhattacharya et al. (2016) also argue that the effectiveness of renewable energy consumption depends on regulatory support and the level of investment in renewable technology. Moreover, political environment and market conditions are also influential in the success of renewable energy consumption in reducing carbon emissions (Marques and Fuinhas, 2012).

South Asia's energy sector is heavily reliant on fossil fuels, as discussed above. However, renewable energy adoption has gained momentum in the recent past as part of efforts directed at climate change mitigation strategies (Asif, Khan and Pandey, 2024). Renewable energy capacity has expanded considerably in India, contributing to a reduction in carbon intensity. Moreover, investments in solar and wind energy in the country have also helped offset carbon emissions despite a steep rise in energy demand (Shahbaz et al., 2021). Rahman and Velayutham (2020) conclude that the impact of renewable energy on carbon emissions in Bangladesh has been modest on account of the meagre share of renewables in the national energy mix. They suggest that financial incentives for clean energy along with enhancing renewable energy infrastructure may enhance the effectiveness of carbon emission reductions. Similarly, Sinha and Shahbaz (2018) stipulate that while renewable energy use is negatively correlated with CO_2 emissions but lack of required infrastructure in the country hinders large-scale renewable energy adoption. Based on the above discussion, it is evident that the share of renewables in total energy consumption remains insufficient across South Asia to alter carbon emission trajectories. Alam et al. (2012) underscore that policy frameworks in the region are not yet robust enough to stimulate large-scale renewable transitions, resulting in continued reliance on fossil fuels for industrial growth and urbanization.

Urban Population and CO_2 Emissions

The rapid expansion of urban areas has significant implications for CO_2 emissions on account of industrial activity, higher energy demand and transportation. Urbanization results in higher fossil fuels consumption for heating, mobility and electricity, thereby accelerating emissions (Wang et al., 2021). Studies have validated the positive relationship between urbanization and carbon emission. For instance, Martínez-Zarzoso and Maruotti (2011) report a positive relationship between the two variables in developing countries, as expansion of urban areas leads to infrastructure development and higher fossil fuel-based energy consumption. Similarly, Wang, Li and Fang (2018) state that the relationship between urbanization and emissions in low- and middle-income countries depends on the stage of economic development. Urbanization has been a key driver of carbon emissions in South Asia. Raihan et al. (2022) argue that a rapid rise in the rate of urbanization in countries like Bangladesh has led to an increase in energy consumption, contributing to higher CO_2 emissions. Similarly, Franco, Mandla and Rao (2017) report that urban expansion in India has resulted in a rise in CO_2 emissions on account of higher energy consumption. Acharya and Acharya (2023) argue that urbanization in South Asia has resulted in a steep rise in carbon emissions and infrastructure development is a major source of these emissions. These studies underscore that while urbanization drives economic growth it necessitates effective policies for sustainable urban development.

Energy Use per Capita and CO_2 Emissions

One of the most direct determinants of CO_2 emission is energy use per capita because literature suggests that higher energy consumption often correlates with increased fossil fuel burning (Andres et al., 2011). Empirical research has shown that rising energy consumption results in higher CO_2 emissions. For instance, Ang (2007) concludes that energy use and CO_2 emissions have a statistically significant positive relationship after analyzing data from 54 countries. Ozturk and Acaravci (2010) also validated Ang's findings and argue that energy efficiency improvements are pivotal for reducing emission. Energy use per capita has increased substantially in South Asia on account of industrialization and urbanization. Some studies have focused on the entire South Asian region and report that fossil fuel-based energy consumption has led to a steep rise in CO_2 emissions in the region (Alom, 2014; Murshed, Ali and Banerjee, 2021), while others have focused on individual countries. For instance, Ahmad et al. (2016) report that energy consumption patterns in India are heavily reliant on fossil fuels, which makes the country a major CO_2 emitter in the region. Bangladesh is no different in this regard as Alam at el. (2012) argue that per capita energy use in the country is on the rise in the country, which drives carbon emissions. Similarly, Lin and Raza (2019) conclude that economic activities along with urbanization have increase energy consumption in Pakistan, which has resulted in increased CO_2 emissions.

Industry Value Added and CO_2 Emissions

Industrial sector is one of the major contributors to CO_2 emissions, particularly in countries undergoing rapid industrialization (Li and Lin, 2015). Industry value-added represents the industrial sector's contribution to GDP and is generally correlated with increased carbon emissions on account of energy-intensive production processes (Lin and Tan, 2017). The relationship between industry value added and CO_2 emissions is intricate and may vary across different contexts. While some studies suggest that industrialization results in a rise in emissions (Wang et al., 2021; Duan et al., 2022; Vatamanu and Cigu, 2022), other suggest a more nuanced relations between the two variables, where industrial value added may not necessarily increase CO_2 emissions (Lin, Omoju and Okonkwo, 2015). Several studies have explored the relation between industry value added and CO_2 emissions in different contexts. For instance, Du et al. (2018) explore this relation in China and report that a higher industry value added to GDP leads to a rise in CO_2 emissions. The study highlights that energy intensive industries are major contributors to emissions in this regard. The relation between industry value-added and CO_2 emissions may vary across developed and developing countries. Industrialization contributes to pollution in both cases but developed countries are more likely to adopt environmentally friendly technologies (Çelik and Deniz, 2009). Like other developing regions, South Asia presents a similar picture. Industrial growth in the region has a positive impact on GDP but it has resulted in a rise in CO_2 emissions (Islam, 2021). Lao and Luo (2024) report that a 1% increase in industrial value added is linked with a 0.7 rise in CO_2 emissions across South Asian economies. Similarly, Sharmin (2022) and Das (2024) find that a higher industry value added to GDP leads to a significant rise in CO_2 emissions across South Asia.

Paris Agreement and South Asia

The Paris Climate Agreement was adopted in December 2015 under the United Nations Framework on Climate Change (UNFCCC) and regarded as a landmark international accord to limit global temperature rise to below 2°C above pre-industrial levels, with efforts to restrict it to 1.5°C (UNFCCC, 2015). It emphasizes voluntary and nationally determined contributions (NDCs), fostering global collaboration in climate action. South Asia is one of the most vulnerable regions to the adverse impacts of climate change on account of its geographical and socioeconomic characteristics (IPCC, 2019). While some countries in this region, like India, Bangladesh. Pakistan and Sri Lanka, have committed to ambitious NDCs, balancing economic growth with environmental sustainability remains a major challenge (Dewasiri et al., 2024).

Research Gaps

While the EKC hypothesis offer valuable insights into the interplay of economic growth and environmental degradation, their applicability to South Asia requires further evidence. Key questions remain regarding the specific roles of urbanization, energy use per capita, renewable energy usage and industry value added in shaping the region's carbon emissions trajectory. While there is substantial literature on the relationship between the above discussed variables and CO_2 emissions, the impact of economic growth (GDP per capita growth) on CO_2 emissions while renewable energy consumption, urbanization, energy use and industry value moderating this relation, particularly in the case of South Asia, has rarely been studied so far. Moreover, there is limited research investigating how the Paris Agreement has influenced CO_2 emissions and related determinants. Existing literature focus more on global or developed regions, leaving a gap in understanding the dynamic relationships between economic activities and environmental outcomes in South Asia post-2015 (Alam et al., 2017). This study aims to fill these gaps by integrating these variables into a comprehensive empirical analysis to provide insights that may not only inform region-specific climate policies but also contribute to literature by providing a holistic analysis of these relationships in the context of a rapidly developing region. The study aims to provide actionable recommendations for sustainable economic growth by integrating theoretical insights with recent empirical data.

Methodology

Data and Variables

This study conducts empirical analysis to determine the impact of key economic and energy variables on CO_2 emission per capita across South Asia. The study uses annual data from 2000 to 2021 from eight countries in the region, namely Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka. The data is retrieved from the World Bank's World Development Indicators database. Table. 1 provides an overview of the variables included in this study. The dependent variable in the analysis is CO_2 emissions per capita (*CO_2_per_capita*), while the independent variables are GDP per capita (*GDP_per_capita*) along with key economic and energy variables like renewable energy consumption (*Renewable_Energy*), urban population (*Urban_Population*), energy use per capita (*Energy_Use*) and industry value added (*Industry_Value*). The analysis encompasses correlation analysis, multiple linear regression and panel data analysis.

Table.1. Source and Description of Variables

Variables	Description	Unit of Measurement	Source
CO_2_per_capita	CO_2 emissions per capita	metric tons	World Bank
GDP_per_capita	Real GDP per Capita	Current US$	World Bank
Renewable_Energy	% of total energy consumption	Percent (%)	World Bank
Urban_Population	Urbanization Rate	Percent of total population	World Bank
Energy_Use	Energy use per capita	Kg of oil equivalent per capita	World Bank
Industry_Value	Industry value added as % of GDP	Percent (%)	World Bank

Empirical Methods

The study follows a sequential modeling approach in line with the study by Shafik and Bandyopadhyay (1992), beginning with *GDP_per_capita* as independent variable in the EKC regression model before integrating variables like *Renewable_Energy*, *Urban_Population*, *Energy_Use* and *Industry_Value* in the multiple linear regression model, it is followed by panel data analysis which estimates the relationship between *CO_2_per_capita* and *GDP_per_capita, Renewable_Energy and Urban_Population*. These analyses are preceded by descriptive statistics to gain insights into the data and correlation analysis to determine the level of association among variables.

EKC Regression Model

The EKC regression model aims at estimating the relationship between CO_2 emission per capita and GDP per capita in South Asia. The model encompasses a quadratic term to test the EKC hypothesis of an inverted U-shaped curve. The proposed model is here as follows.

$$CO_2\_per\_capita = \beta_0 + \beta_1.GDP\_per\_capita + \beta_2.GDP\_per\_capita\hat{}2 + \varepsilon$$

where *CO_2_per_ capita* is the dependent variable, *GDP_per_capita* is the independent variable, β_0 is the intercept, β_1 represents the marginal effect of GDP per capita on CO_2 emissions per capita, β_2 represents the non-linear relationship by examining the quadratic term. It aims to determine whether CO_2 emissions show a turning point behavior as GDP increases, as stated in the EKC framework and ε is the error term.

The model includes only *GDP_per_capita* as it follows the theoretical foundation of the EKC hypothesis and simplifies its interpretation. *GDP_per_capita* and its squared term form the core of the EKC framework and provide a fundamental test of whether an inverted U-shaped curve exists in the data. The inclusion of additional variables at this stage may obscure the primary relationship between economic growth and pollution. Grossman and Krueger (1995), Panayotou (1997), Stern (2004) and Dinda (2004) also employed GDP per capita and environmental degradation in their studies to test the EKC hypothesis. Moreover, starting with a simpler model helps avoid multicollinearity and complexity that may arise from including several variables (Perman and Stern, 2003). It allows for clearer interpretation of the direct impact of GDP.

Multiple Linear Regression Model

To provide a more comprehensive coverage to the aforementioned relationship between *CO_2_per_capita* and *GDP_per_capita*, three other key variables are included in a multiple linear regression model. Several studies like Saboori and Sulaiman (2013), Alam at al. (2017) and Balsalobre-Lorente et al. (2018) have employed multiple linear regression analysis to determine the impact of different economic and/or energy variables on emissions.

The regression model for this study is as follows:

$$\begin{aligned} CO_2\_per\_capita = \beta_0 + \beta_1.GDP\_per\_capita + \beta_2.Renewable\_Energy + \\ \beta_3.Urban\_Population + \beta_4.Energy\_Use + \\ \beta_5.Industry\_Value + \varepsilon \end{aligned}$$

Where:

CO_2_per_capita is the dependent variable, *GDP_per_capita, Renewable_Energy, Urban_Population, Energy_Use and Industry_Value* are independent variables. $\beta_0, \beta_1, \beta_2 \ldots\ldots \beta_5$ are coefficient estimates, and ε is the error term.

Panel Data Analysis

This study compliments regression analysis with panel data analysis as the former may overlook unobserved heterogeneity, potentially resulting in biased estimates. Panel data analysis has the ability to account for such heterogeneity by introducing fixed and/or random effects. These effects control for country specific factors that remain constant over time. Furthermore, it may provide more reliable estimates on account of additional data points, which may enhance estimates' efficiency and reduce issues linked with multicollinearity. Amin, Song and Farrukh (2022), Ashiq, Ali, Siddique (2023).and Adeleye et al. (2023) employed panel data analysis to determine the determinants of carbon emissions in South Asia.

Panel data shows changes within countries over time and reveals dynamic relationships between variables. It may also reduce omitted variable bias by controlling for time-variant and time-invariant effects, influencing CO_2 emissions per capita. Fixed and random effects models also include individual intercepts in the form of fixed effects and/or random variations across countries in the form of random effects that may distort the results otherwise. As the dataset used in this study includes 8 countries across 22 years, panel data analysis creates a balanced panel with cross-sectional and time series data. Similar to the multiple linear regression model, the dependent variable is CO_2_per_capita and the independent variables are *GDP_per_capita*, *Renewable_Energy*, *Urban_Population*, *Energy_Use* and *Industry_Value*. Panel data analysis includes a structural break in 2015 on account of the *Paris Agreement*. It is included in the analysis to determine whether this agreement has any impact on the relationship between CO_2 emissions per capita and GDP per capita in South Asia. It is included as a dummy variable in the model

To decide between fixed effects and random effects models, a Hausman test is performed. If individual effects are correlated with the predictors, a fixed effects model is preferred. Otherwise, a random effects model is a better alternative.

The model is here as follows;

$$CO_{2it} = \alpha_i + \beta_1.GDP\_per\_capita_{it} + \beta_2.Renewable\_Energy_{it} + \beta_3.Urban\_Population_{it} + \beta_4.Energy\_Use_{it} + \beta_5.Industry\_Value_{it} + \beta_6.Paris\_dummy_{it} + \mu_{it}$$

Where:

α_i represents fixed or random effects depending on the choice made after the Hausman test. It is included in the model to account for time-invariant/variant country characteristics that may influence CO_2 emissions. $\beta_1, \beta_2 \ldots\ldots \beta_6$ are the coefficients of the respective independent variables and β_6 is the coefficient of the dummy variable.

GDP_per_capita$_{it}$ is the Gross Domestic Product per capita for country i at time t. *Renewable_Energy*$_{it}$ is the proportion of energy derived from renewable sources for country i at time t. *Urban_Population*$_{it}$ is the percentage of urban population for country i at time t. *Energy_Use*$_{it}$ is the energy use per capita for country i at time t. *Industry_Value*$_{it}$ is the industry value added as percent of GDP for country i at time t.

Paris_dummy$_{it}$ is a dummy variable representing the Paris Agreement, where 0 for years before 2015 and 1 for 2015 and beyond. μ_{it} represents the error term.

Data is analysed through R version 4.4.2.

Results and Discussion

This section presents results from the estimated methods discussed in the methodology part of this study.

Descriptive Statistics

Descriptive statistics depicted in Table.2 provide a summary of the variables included in this study. These statistics demonstrate considerable economic and energy use disparities across South Asia, which are pivotal for understanding region-wide CO_2 emissions trends and for designing differentiated policy measures.

Table.2 Descriptive Statistics

Variables	Mean	Median	St. Deviation	Minimum	Maximum
CO_2_per_capita (metric tons)	1.077	0.765	1.053	0.039	5.323
GDP_per_capita (USD)	2041.23	1161.28	2306.04	142.90	11349.85
Renewable_Energy (%)	47.418	46	27.513	1.2	92
Urban_Population (%)	28.446	29.639	7.817	13.397	43.008
Energy_Use	6244.09	3637.16	7034.59	204.23	27785.35
Industry_Value	23.317	23.810	8.494	8.058	41.621

The wide range of *CO_2_per_capita* values, combined with a high standard deviation reveals significant variations across South Asia and in different years. It reflects diverse levels of industrialization and energy consumption patterns in the region. *Renewable_Energy* values suggest that renewable energy contributes significantly to the energy mix in the region but the wide range reflects considerable disparities in renewable energy adoption across countries. Moreover, the large standard deviation relative to the mean of *GDP_per_capita* indicates wide economic inequality in South Asia. The wide range reflects different stages of economic development in different countries. Urbanization has also a wide range (13.4% to 43%), which shows varying levels of urban expansion, affecting energy use and emissions patterns differently across the region. Furthermore, *Energy_Use* per capita shows a large disparity, depicted from the minimum and maximum values along with a high standard deviation. It suggests heterogeneity in energy consumption habits, possibly driven by industrialization, energy efficiency and economic status. Industrial contribution demonstrates moderate variation, with a mean value of 23.32%, ranging from 8% to 41%. It reflects structural differences in the dependence of the economies on industrial sectors.

Correlation Analysis

The correlation matrix shown in Figure. 1 reveals the relationships among variables included in this study. The matrix depicts strong positive correlation between *CO_2_per_capita* and *GDP_per_capita*, suggesting that higher GDP per capita is linked with higher CO_2 emissions, potentially due to industrialization and other economic activities. A strong positive correlation also exists between *CO_2_per_capita* and *Energy_Use,* indicating that a rise in energy use is associated with higher CO_2 emissions. Moreover, *GDP_per_capita* and *Energy_Use* have also a strong positive correlation. It shows that relatively wealthier countries tend to use more energy.

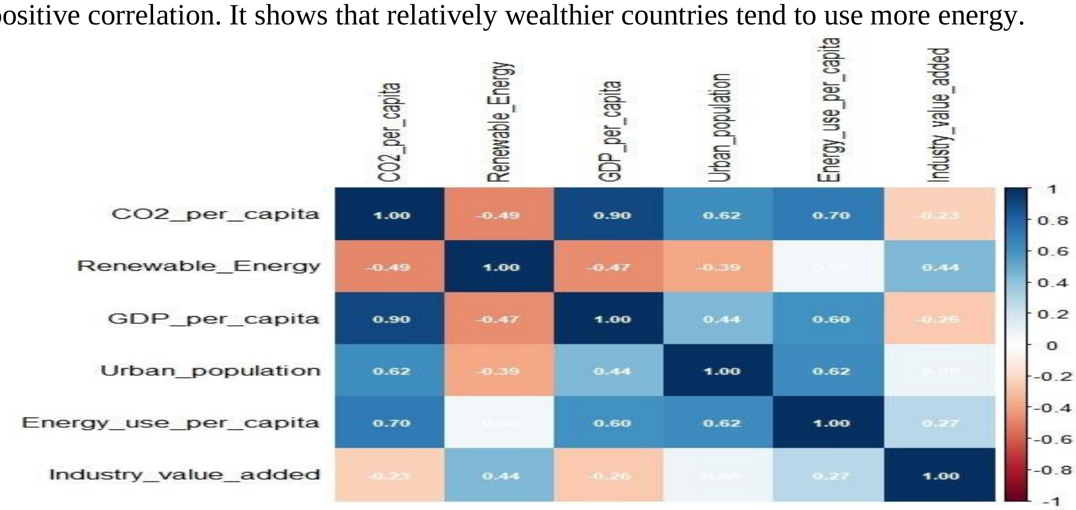

Figure 1. Correlation Matrix

In contrast to the above positive correlations, *CO_2_per_capita* and *Renewable_Energy* has a negative correlation, suggesting that high reliance on renewable energy is linked with lower CO_2 emissions. Interestingly, *Renewable_Energy* is also negatively correlated with *GDP_per_capita* and *Urban_Population*. It shows that countries with higher GDP rely less on renewable energy. It could be due to existing investments in non-renewable infrastructure. Negative correlation with urbanization is possibly due to high energy demands in cities.
Figure.1 shows that *Urban_Population* has a moderate positive correlation with *CO_2_per_capita* and a weak positive correlation with *GDP_per_capita*. It shows that urban areas emit higher emissions. Furthermore, Industry Value added has a weak positive correlation with renewable energy, indicating that some industrial sectors in the region have incorporated renewable energy to a certain extent. *Industrial_Value* has a weak negative correlation with *CO_2_per_capita*. It shows that industrialization may not be the sole heavy contributor to CO_2 emissions, potentially reflecting varied industrial technologies and compositions.

EKC Regression Model

The EKC regression model is employed to investigate the relationship between *CO_2_per_capita* and *GDP_per_capita* in South Asia, incorporating a quadratic term to assess the non-linear behavior postulated by the EKC hypothesis. The model's results provide interesting insights into the relationship between *GDP_per_capita* and *CO_2_per_capita* as shown in Table.3. The high R-squared value (0.81) shows that *GDP_per_capita* is able to explain a significant portion of the variance in *CO_2_per_capita*. The coefficient for GDP per capita is also positive and highly significant, suggesting that as income level rises, *CO_2_per_capita* also increases initially. It aligns with the early upward phase of the EKC, where economic growth results in higher resource use and pollution. The quadratic term's coefficient is negative and statistically insignificant, implying that there is no clear evidence of a turning point (inverted U-shape curve) for *CO_2_per_capita* within the observed *GDP_per_capita* range. This finding aligns with Stern (2004), who is of the view that turning point of the curve may only be found in case of developed countries. Pao and Tsai (2010) also conclude that there is a positive relationship between CO_2 emissions and economic growth but the quadratic term remains insignificant.

Table.3. EKC Model Results

Coefficients	Estimate	Std. Error	t-value	Pr (> | t |)
(Intercept)	1.851 e-01	6.354 e-02	2.913	0.00406 **
GDP_per_capita	4.622 e-04	4.632 e-05	9.979	< 2e-16***
$(GDP\_per\_capita)^2$	-5.381 e-09	4.794 e-09	-1.122	0.26331

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 0.4525 on 173 degrees of freedom
Multiple R-squared: 0.8178, Adjusted R-squared: 0.8157
F-statistic: 388.2 on 2 and 173 DF, p-value: < 2.2e-16

Since the EKC model does not confirm a significant turning point in South Asia, it indicates that either South Asian countries have not reached income levels high enough to experience a decline in emissions as suggested by the EKC hypothesis or economic growth alone may not result in lower emissions in this region. It supports the view that in the absence of targeted environmental policies and investment in cleaner technologies, economic growth may continue to drive emissions. These findings are consistent with Stern (2004), who stressed the importance of technology, structural changes and policy interventions in reducing emissions beyond a certain income level. The findings are also in line with Dinda (2004) and Stern (2017) who are of the view that EKC is context dependent and regional differences in industrial composition, environmental awareness and regulatory frameworks affect the relationship between income and pollution. Figure. 2 shows that at lower levels of *GDP_per_capita*, *CO_2_per_capita* are relatively low but as GDP rises, emissions also increase, possibly due to industrialization, and high energy use. The graph stops at a point where the curve seems to level out, which suggests that the relationship between economic growth and CO_2 emissions continues to rise linearly at higher GDP levels.

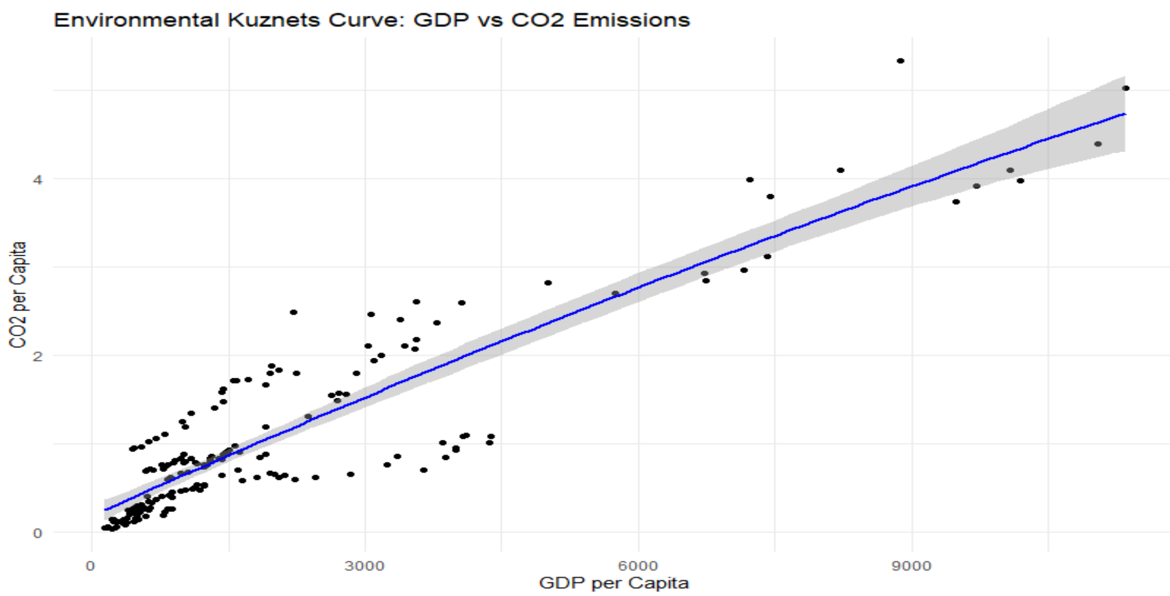

Figure. 2 Environmental Kuznets Curve: GDP vs CO_2 Emissions (South Asia)

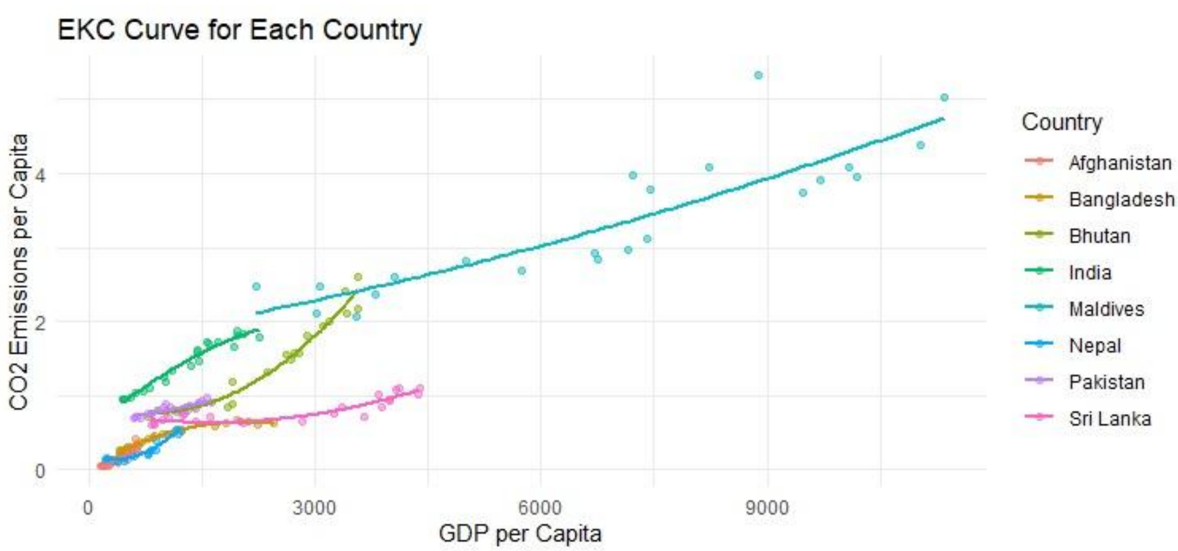

Figure. 3 Environmental Kuznets Curve: GDP vs CO_2 Emissions (Country-Wise Analysis)

Country wise EKC analysis provides interesting insights. Figure. 3 reveals that India (olive green curve) follows an uptrend trend with higher GDP and increasing emissions, suggesting growing industrialization. However, no

signs of an inverted U-shaped curve could be observed. Pakistan (purple curve) shows moderate GDP growth with increasing emissions, indicating industrial expansion. Similarly, Bhutan (green curve) and Bangladesh (red curve) depict moderate GDP growth with a steady rise in CO_2 emissions. However, Sri Lanka (magenta curve) is showing relatively stable emissions, indicating controlled economic and environmental policies. Nepal (pink curve) and Afghanistan (orange curve) have low GDP growth and lower emissions, suggesting minimal industrialization in these countries. Maldives (light blue) has the highest GDP per capita in the region, showing a rising trend in CO_2 emissions.
The insignificant quadratic term suggests the need to explore additional factors for a more comprehensive understanding of emissions trends. Therefore, this study employs a multiple regression model, in which additional key economic and energy variables are used.

Multiple Linear Regression Model

The multiple linear regression model for this study encompasses *CO_2_per_capita* as the dependent variable, while *GDP_per_capita*, *Renewable_Energy*, *Urban_Population*, *Energy_Use* and *Industry_Value* are independent variables.
Table. 4 represents results of the regression model. The R-squared value (0.905) shows that the model explains 90.5% of the variation in *CO_2_per_capita* emissions, indicating a strong fit. It shows that the independent variables are highly explanatory of CO_2 emissions in the region.

Table.4. Multiple Linear Regression Model Results

Coefficients	Estimates	Std. Error	t-value	Pr (> | t |)
Intercept	5.328 e-01	1.997 e-01	2.694	0.00776**
GDP_per_capita	2.396 e-04	1.972 e-05	12.146	2 e-16***
Renewable_Energy	-6.247 e-03	1.466 e-03	-4.261	3.36 e-05***
Urban_Population	1.361 e-02	5.110 e-03	2.663	0.00850 **
Energy_Use	5.568 e-05	7.509 e-06	7.415	5.49 e-12***
Industry_Value	-1.641 e-02	3.650 e-03	-4.495	1.28 e-05***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Residual standard error: 0.3246 on 170 degrees of freedom
Multiple R-squared: 0.9079, Adjusted R-squared: 0.9052
F-statistic: 335.1 on 5 and 170 DF, p-value: < 2.2e-16

The coefficient of *GDP_per_capita* is positive and considerably higher, indicating that economic growth is strongly associated with CO_2 emissions. The higher negative coefficient for renewable energy shows that renewable energy has a negative impact on emissions. These findings align with Shahbaz et al. (2013), who found that GDP per capita is positively related with carbon emissions and renewable energy consumption is negatively related with emissions in case of Indonesia. Moreover, the positive coefficient of Urban Population reveals that urbanization leads to higher CO_2 emissions. Poumanyyong and Kaneko (2010) also found that urbanization results in higher emissions in developing countries. The model's results also suggest that *Energy_Use* per capita is also a major driver of emissions in the region. The stronger t-value suggests acute dependence on energy use for CO_2 emissions along with inefficient energy use. However, *Industry_Value* added has a negative coefficient, showing that industrial sectors are not the only major contributor to emissions in South Asia. These results confirm the findings by Al-Mulali et al. (2015), who concluded that energy consumption and urbanization drive emissions and industrialization show mixed impact on CO_2 emissions.

Multiple Linear Regression Model Diagnostics

Variance Inflation Factors (VIF)

VIF measures the inflation of a variable's variance on account of multicollinearity. A rule of thumb is that if its value is lower than 5, it has low to moderate multicollinearity, while a value above 5 is an indication of high multicollinearity (Stine, 1995). Table. 5 shows the VIF values for the independent variables included in this study. None of the variables show high multicollinearity.

Table. 5. VIF Values for Independent Variables

Variable	VIF Value	Interpretation
GDP_per_capita	3.44	Moderate multicollinearity, acceptable
Renewable_Energy	2.70	Low Multicollinearity, no concern
Urban_Population	2.65	Low Multicollinearity, no concern
Energy_Use	4.63	Moderate multicollinearity, acceptable
Industry_Value	1.60	Low Multicollinearity, no concern

Residuals

Residuals histogram as shown in Figure. 4 reveal that residuals are mostly centred around zero. It indicates that the model's predictions neither overestimate nor underestimate CO_2 emissions per capita in South Asia. However, the histogram shows slight skewness to the right, suggesting that some predictions may have larger positive errors. The spread of residuals is fairly even, revealing there is no major pattern indicating heteroscedasticity. Furthermore, a small bar to the far right can be observed in the figure, with relatively large positive residuals. These could be outliers, where the model overestimates emissions. Nevertheless, the residuals show a reasonably good fit for the model.

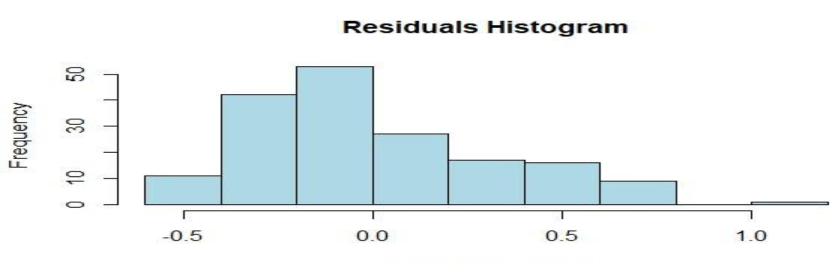

Figure. 4. Residuals Histogram

Normal Q-Q Plot

Normal Q-Q plot is employed to examine whether the residuals of the regression model follow a normal distribution. Ideally, the residuals need to align closely with 45˚ red reference line, showing normality (Ben and Yohai, 2004). Figure. 5 shows that most of the residual points fall near the red line, indicating that the residuals are approximately normally distributed, with some minor deviations. This supports the assumption of normality in the regression model used in this study.

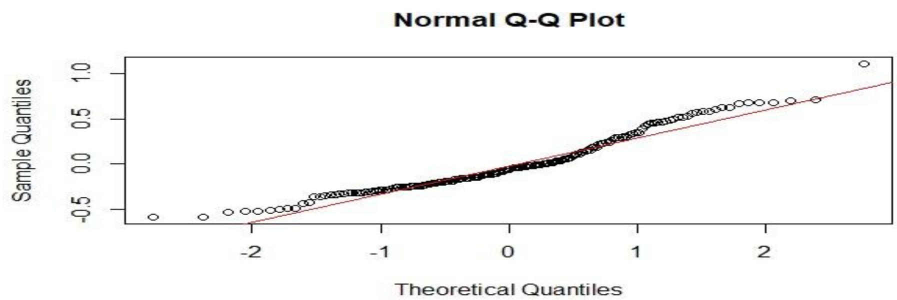

Figure. 5. Normal Q-Q Plot

Actual vs Predicted CO_2 Emissions

The actual vs predicted CO_2 emissions plot is an important tool to evaluate the performance of the regression model. Figure. 6 shows that besides some minor deviations, the data points closely follow the 45-degree dashed line, suggesting that the model has made relatively accurate predictions. It suggests that the independent variables are good predictors of CO_2 emissions in South Asia.

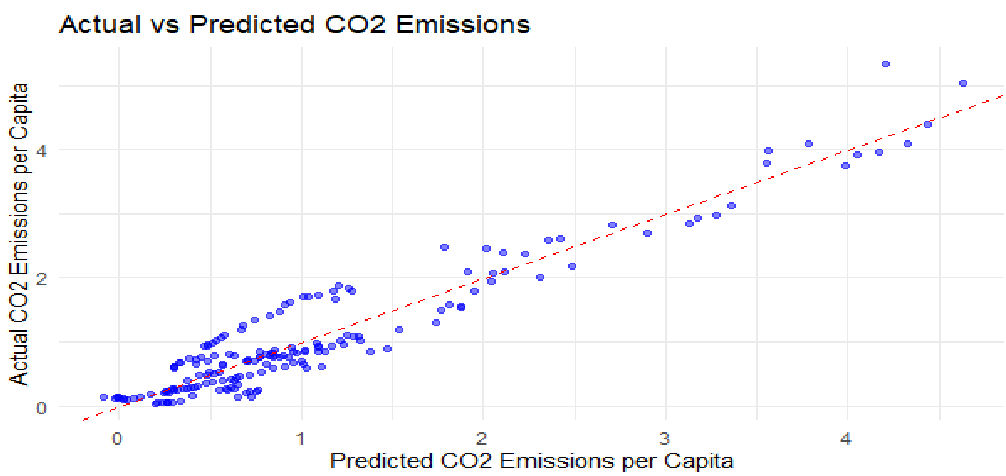

Figure. 6. Actual vs Predicted CO_2 Emissions

Panel Data Analysis

Panel data analysis enables us to account for heterogeneity overlooked by regression analysis. The analysis encompasses fixed or random effects, controlling for country specific factors and providing more data points. Thus, enhancing the efficiency of estimates along with reducing multicollinearity. Panel data analysis model estimates the relationship between *CO_2_per_capita* and key independent variables, namely *GDP_per_capita, Renewable_Energy, Urban_Population, Energy_Use and Industry_Value*.

Hausman Test

A Hausman test is performed to determine the preferred model between fixed and random effects models. The null hypothesis is that the random effects model is appropriate. If the p-value is less than 0.05, the null hypothesis is rejected. The results show a p-value of 0.02547 and the null hypothesis is rejected. It suggests that there is correlation between the regressors and the individual-specific-effects as shown in Figure. 7. It can be concluded that the fixed effects model is the appropriate choice for this analysis.

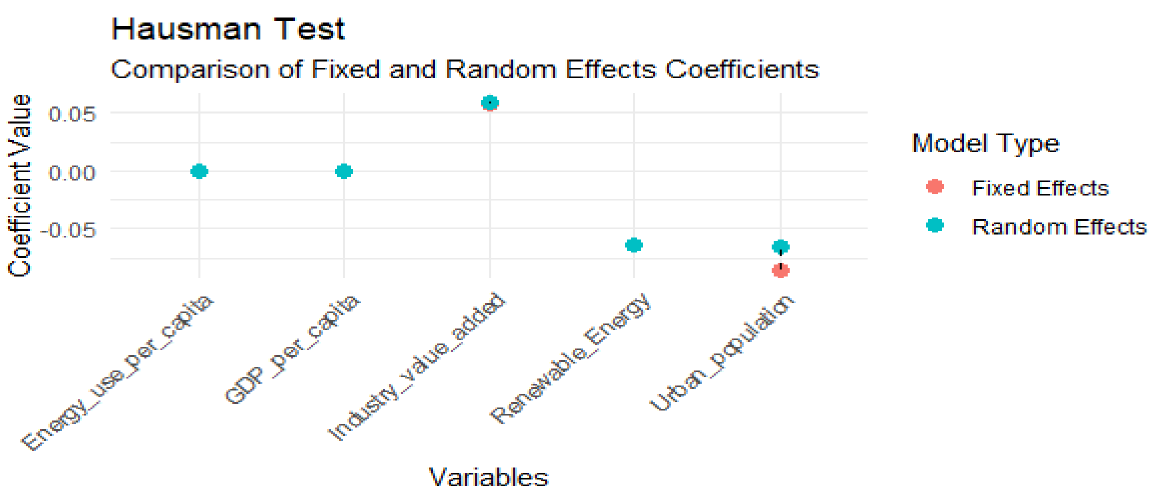

Figure. 7. Hausman Test

Table. 6 show results of the panel data analysis. The model as a whole is statistically significant and explains a large portion of variance in CO_2 emissions in South Asia. It is evident from the table that the coefficient of *GDP_per_capita* is positive and statistically significant, indicating that higher GDP per capita results in higher emissions. The strong positive relationship is in alignment with the EKC in its early stage, where economic growth results in higher emissions.

Unlike the multiple linear regression model, renewable energy has a positive but insignificant impact on CO_2 emissions. It means that renewable energy consumption does not have a statistically significant impact on emissions in South Asia. Moreover, urbanization has a positive but insignificant impact on emissions. Energy use per capita has a positive and statistically significant coefficient, suggesting that higher energy use results in higher emissions. Industry value has a negative and statistically significant coefficient like the regression model, indicating that higher industry value added is linked with lower emissions. The Paris Agreement dummy variable is positive but statistically insignificant. It shows that the Paris Agreement has not significantly impacted emissions trends in the sample period. This variable captures the structural break in 2016. The lack of significance indicates that the agreement's policies have not led to immediate measurable changes in CO_2 emissions. It is common, as policy impacts often take several years to manifest (Aldy et al., 2016).

Table. 6. Panel Data Analysis Results

Coefficients	Estimate	Std. Error	t-value	Pr (> | t |)	Significance
GDP_per_capita	1.8562 e-04	1.7623 e-05	10.5329	< 2.2 e-16 ***	Highly Significant
Renewable_Energy	3.5459 e-04	3.0350 e-03	0.1168	0.907136	Not Significant
Urban_Population	1.5524 e-02	9.7203 e-03	1.5971	0.112191	Not Significant
Energy_Use	5.3911 e-05	8.6257 e-06	6.2500	3.489 e-09 ***	Highly Significant
Industry_Value	-1.7244 e-02	5.2505 e-03	-3.2843	0.001253 **	Significant at 1%
Paris_dummy	1.3661 e-02	4.7198 e-02	0.2894	0.772611	Not Significant

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
Total Sum of Squares: 30.057
Residual Sum of Squares: 5.7102
R-Squared: 0.81002
Adj. R-Squared: 0.79478
F-statistic: 115.122 on 6 and 162 DF, p-value: < 2.22e-16

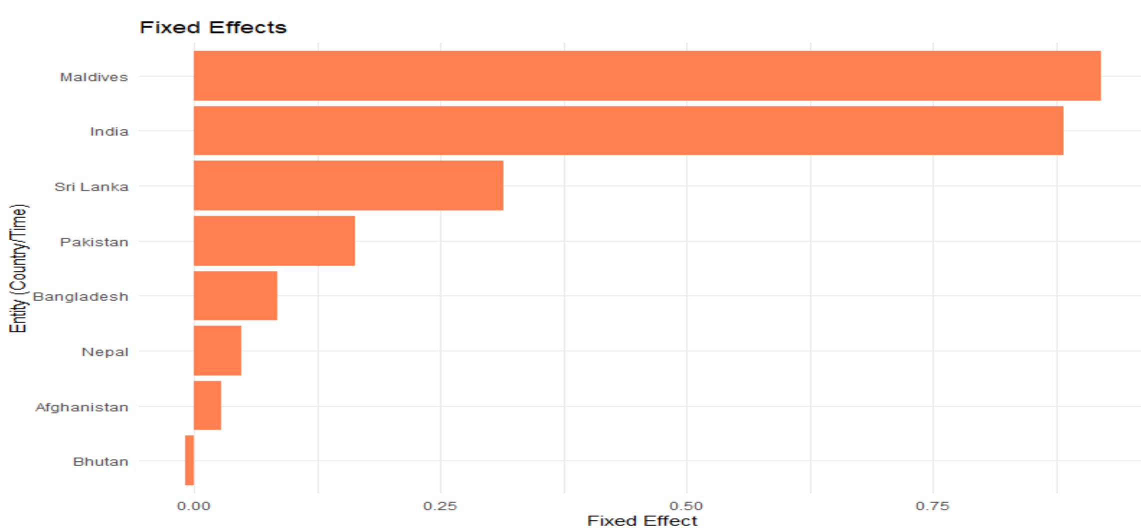

Figure. 8. Fixed Effects (country wise)

Figure.8 highlights the varying importance of country-specific fixed effects across 8 South Asian countries in determining CO_2 emissions per capita in the region. It is evident in the figure that Maldives has the highest fixed effects, indicating that country-specific factors in Maldives have a strong influence on CO_2 emissions per capita relative to other countries. India follows with a slightly lower but significant fixed effects, suggesting that India's specific characteristics also play a vital role in determining CO_2 emissions in the region. Sir Lanka's fixed effects are also significant but lower than Indian and Maldives. However, rest of the countries, i.e., Pakistan, Bangladesh, Nepal and Afghanistan show progressively lower fixed effects. These countries have less of an impact on CO_2 emissions per capita. Bhutan has very low fixed effects, implying that the country's specific characteristics have the least impact on emissions in the region.

Conclusion

This study explored the EKC hypothesis and analyzed the key determinants of CO_2 emissions in South Asia using different econometric models. The EKC analysis showed that GDP per capita is a major driver of CO_2 emissions, consistent with economic development being linked to environmental deterioration. However, the squared term of GDP per capita did not show statistical significance, suggesting the absence of a turning point in emissions with a rise in income. This finding challenges the applicability of the EKC hypothesis to South Asia, where emissions continue to rise as economies develop. Another interpretation could be that the turning point predicted by the EKC has not yet reached. It highlights the importance of integrating sustainable development policies to decouple economic growth from environmental degradation. The multiple linear regression model underscored the intricate relationships between CO_2 emissions and several key variables. Renewable energy was found to have a mitigating effect on emission, highlighting its potential in reducing environmental degradation. However, urbanization and energy use per capita have a positive impact on emissions, which reflects the challenges posed by rapid urbanization and increasing energy demand. Industry value added also contributes to emissions, emphasizing the need for sustainable industrial policies in South Asia. The panel data analysis added a policy dimension to the analysis by including the Paris Agreement through a dummy variable. Although this variable provided insights into the impact of international climate commitments, the findings suggest that the agreement's impact on emissions in the region remains limited. This underscores the need for stronger implementation and enforcement of climate policies to achieve tangible results. Future research needs to expand the scope by including additional variables to provide a more comprehensive understanding of emissions dynamics. Additionally, extending the dataset to include post-2020 data may allow for evaluating the full impact of the Paris Agreement and other recent policy initiatives. Policymakers need to prioritize renewable energy deployment as a key strategy for reducing carbon emissions while fostering economic growth. Urbanization also needs low-carbon planning and the integration of sustainable infrastructure to manage emissions effectively. South Asian countries should strengthen their climate commitments by adopting more ambitious policies in line with the Paris Agreement. Regional cooperation in technology transfer and capacity building may also play a vital role in supporting the transition to a low-carbon economy. By addressing these challenges, South Asia can manage a balance between economic development and environmental sustainability, contributing meaningfully to global climate goals. This study provides a foundation for policymakers and researchers to design strategies that align with sustainable development objectives while meeting international climate commitments.

Declaration

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Conflict of interest: N/A

Ethics approval/declaration: N/A

Consent to participate: N/A

Consent for publication: N/A

Data availability: Data available on request

Authors contribution: The author was solely involved in all aspects of this work, including the study's conceptualization and design, data collection, analysis and interpretation of results, and the preparation of the manuscript.

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