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*Research article*

## **Energy poverty, economic growth and environmental degradation in South Asia: Do energy resources matter?**

**Memona Rasheed<sup>1</sup>, Hooi Hooi Lean<sup>2,\*</sup> and Nam Foo<sup>3</sup>**

<sup>1</sup> Economics Program, School of Social Sciences, Universiti Sains Malaysia, Penang, Malaysia

<sup>2</sup> Faculty of Economics, Business and Accounting, i-CATS University College, Kuching, Malaysia

<sup>3</sup> School of Business and Law, Edith Cowan University, Perth, Australia

\* **Correspondence:** Email: [learnmy@gmail.com](mailto:learnmy@gmail.com).

**Abstract:** Developing countries can combat energy poverty by enhancing renewable energy and economic growth with minimal adverse environmental effects. In this paper, we present a comprehensive analysis of energy poverty, renewable energy, economic growth, carbon dioxide emissions, and urbanization (URB) in South Asian countries from 1990 to 2021, focusing on Pakistan, India, Bangladesh, and Sri Lanka. We employed econometric analysis techniques like Panel Pooled Mean Group (PMG)- Autoregressive Distributed Lag (ARDL), Fully Modified Ordinary Least Squares (FMOLS), and Dynamic Ordinary Least Squares (DOLS) to provide empirical results, as they enable panel data and control for endogeneity. The findings suggested that the fight against energy poverty and the progress of economic growth need not be detrimental to the environment. Our results indicated that authorities can bring about positive change by promoting green sanitation, which involves using renewable energy sources in sanitation systems and combating energy poverty with renewable energy. These findings are significant in understanding the complex interplay between energy poverty, economic growth, and environmental deterioration, and they provide a hopeful basis for developing effective policies to address energy poverty, economic growth, and environmental degradation.

**Keywords:** energy poverty; energy resources; environmental degradation; South Asia

**JEL Codes:** Q01, Q41, Q53, Q54, O13

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## 1. Introduction

The Paris Agreement of 2015 and the Sustainable Development Goals (SDGs) for 2016 are international initiatives that focus on clean energy access, economic growth, and preservation of the environment. These agreements are particularly relevant to this paper as they underscore the importance of addressing energy poverty and promoting sustainable economic growth. The Paris Agreement and SDGs recognize that it is essential to enable people to have energy access, encourage economic development, and save the world from environmental degradation (Dogan et al., 2019). This demonstrates an integrated approach toward sustainable development by considering social, economic, and environmental factors. Moreover, fossil fuels have been used to enhance economic growth in regions with limited energy supply. This means using fossil fuels has increased pollution, leading to environmental degradation (Zhao et al., 2021).

Nonetheless, economic growth may raise environmental concerns because carbon emissions and other pollutants usually accompany them are significant causes of global warming. However, fossil fuel emissions contradict the notion of eco-friendly growth despite their contribution to GDP growth (Sy & Mokaddem, 2022). Although fossil fuels have contributed to economic growth, it is essential to recognize that their use negatively impacts climate change and sustainability (Sy & Mokaddem, 2022). To achieve sustainable energy consumption, there must be a transition from using polluting energy sources like oil or coal to renewable energy (RE) sources. This transition plays a vital role in providing consumers with universal access to affordable energy. It is crucial to achieve a sustainable global economy through clean energy sources while aligning with the goals of the Paris Agreement and the SDG agenda. As part of this transition, the ‘Next Generation Energy Strategy’ outlines a comprehensive plan for shifting to renewable energy sources and reducing reliance on fossil fuels.

Furthermore, raising awareness about environmental degradation is essential to speed up the worldwide transition to eco-friendly energy sources and achieve sustainable development. However, energy poverty (EP), defined as the absence of access to modern, clean energy services at affordable rates poses another pressing concern for developing nations that depend on nonrenewable energy sources (Nathaniel & Adeleye, 2021). Using renewable energy sources by promoting solar plants and decentralized energy systems present a promising solution to energy poverty and environmental degradation.

Therefore, we present new knowledge about energy poverty, different energy resources, economic growth, and their effects on environmental degradation in South Asian countries during 1990–2021. Bangladesh, Pakistan, India, Nepal, and Sri Lanka are chosen for this study because they have significant energy poverty challenges, varied energy resource profiles, and accessible data. The findings of this study offer recommendations for future studies on contemporary energy poverty, energy supply, economic growth, and environmental effects, enlightening and informing the academic community and policymakers about these issues. We explore the serious policy challenge of maintaining a balance between economic growth and environmental degradation in South Asia’s energy-poverty context. We are expected to offer solutions by examining how energy poverty and economic development contribute to environmental deterioration in South Asia. Evidence-based insights will be provided to highlight opportunities and problems relevant to the region. Our overarching objective is to help policymakers reach sustainable development goals by reducing environmental degradation and increasing access to energy for all. Furthermore, we intend to promote regional collaboration by tackling common challenges and suggesting frameworks for collaborative action.

This research is necessary because of the ongoing challenge of energy poverty in South Asia, which affects millions by limiting access to clean and inexpensive energy. Furthermore, the region's rapid economic growth has caused environmental degradation, raising serious concerns about climate change, such as severe weather and resource depletion. Sustainable development necessitates balancing economic growth, energy availability, and environmental protection. The study bridges this research gap, providing crucial insights to drive policies that promote economic growth, reduce environmental degradation, and strengthen regional collaboration to address common concerns.

This research underscores the urgency of tackling environmental problems by addressing CO<sub>2</sub> emissions through clean energy use. Environmental pollution is a stark signal of environmental decline, a harmful alteration of the environment caused by human actions, including changing energy sources, toxic radiation, and the composition of substances. A decrease in plant life and biodiversity, harmful levels of toxic substances in the air and crops, heightened chance of environmental disasters, and endangerment of life-support systems indicate a deterioration in environmental quality caused by pollution. Air pollution poses a significant and dangerous risk to the environment, humans, animals, plants, and other organisms. The destruction of the ozone layer is a worldwide environmental issue causing a heightened greenhouse gas effect, acid rain, and climate change. Immediate and resolute action is necessary and crucial to confront this problem. It is clear that addressing environmental pollution is urgent, and taking immediate action is essential to avoid additional harm to our planet. It is up to all of us to take action immediately, emphasizing the need for immediate action and the urgency of the situation.

There are four ways in which this research contributes to the literature. First, we focus on the relationships between critical variables in the region, namely EP, RE/NRE, CO<sub>2</sub>, and URB. Second, we break down energy resources into RE and NRE, which facilitates examining the impact of energy resources on the environment in South Asian countries. Thus, this research can be used as a guide for understanding the situation in other emerging countries. Despite the environmental challenges in South Asian countries, the potential advances in renewable energy present significant chances for a more sustainable future.

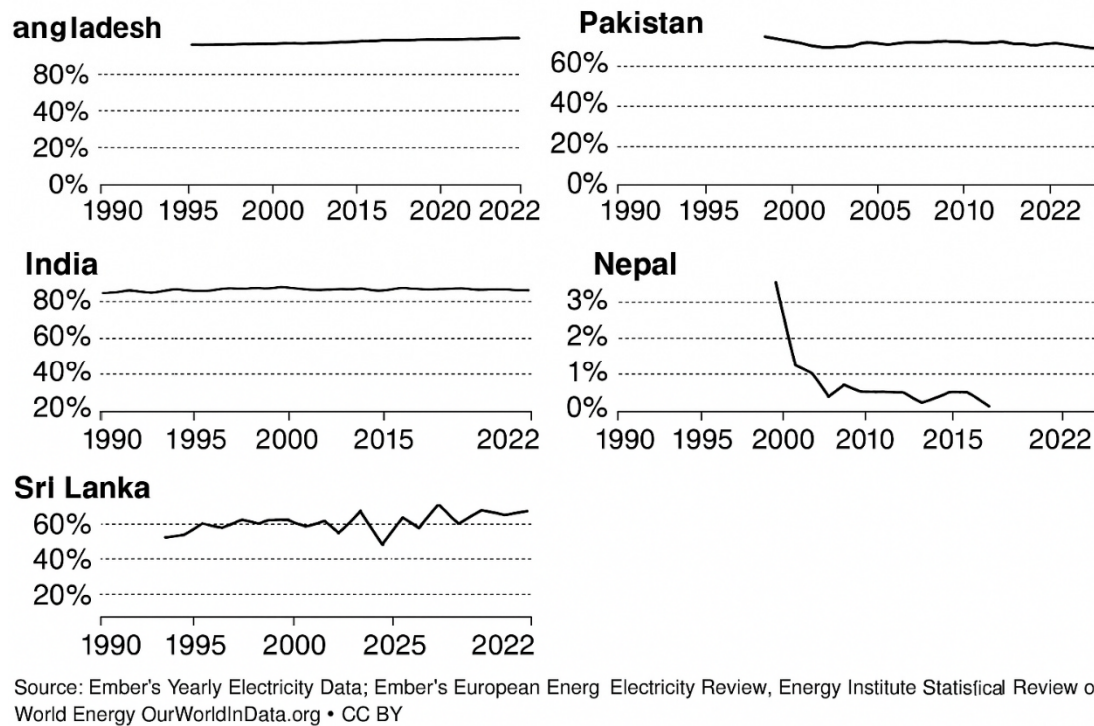
This study reveals the effects of the lack of clean energy access on the environment. To decrease energy poverty, increase economic growth, and prevent environmental degradation justifies the need for this study. In addition, our findings will benefit society, considering that increasing economic growth, decreasing energy poverty, and saving the environment are the major concerns in today's world. The study's framework, methodology, data, results, discussion, and conclusion provide a comprehensive understanding of the issue. In Section 2, we open with a synopsis of the prior material. Section 3 includes the framework of the study. Section 4 represents the methodology and data. In Section 5, we review the results and discussion. Section 6 consists of a conclusion with some recommendations. Our findings are significant for the current understanding of the issue and provide a valuable foundation for future research.

## **2. Literature review**

The literature review is divided into three parts: 2.1 South Asian Countries at a Glance, 2.2 The Theoretical Literature Review, and 2.3 The Empirical Literature.

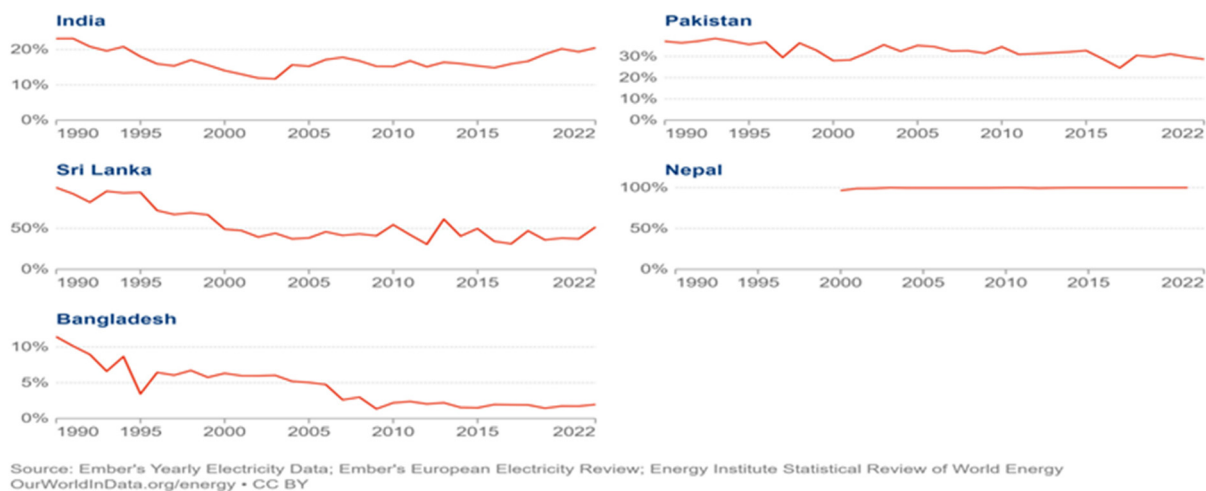
## 2.1. South Asian Countries at a Glance

Energy poverty is a major significant issue in South Asian countries. Due to the use of non-renewable energy sources, energy poverty causes environmental degradation. Figure 1 illustrates the alarming increase in non-renewable energy usage in all nations, with Nepal being the only exception from 1990 to 2022. This surge is a cause for concern, leading to environmental challenges that demand immediate and effective environmental solutions.



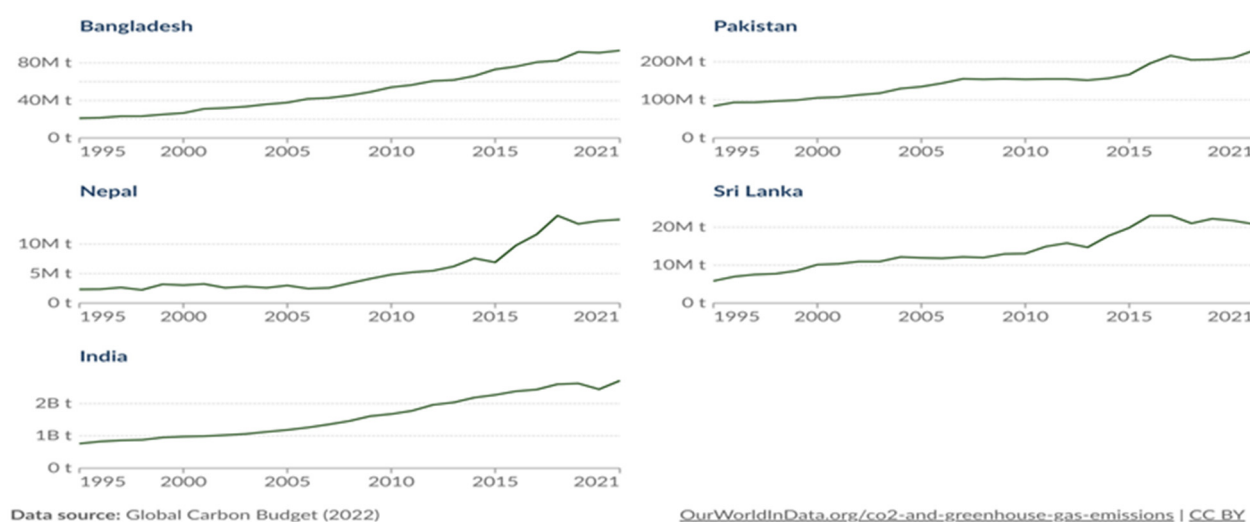
**Figure 1.** Nonrenewable energy consumption in South Asian nations.

Figure 2 reveals renewable energy consumption in South Asian nations, which has decreased except for Nepal during the selected time period.



**Figure 2.** Renewable energy consumption in South Asian nations.

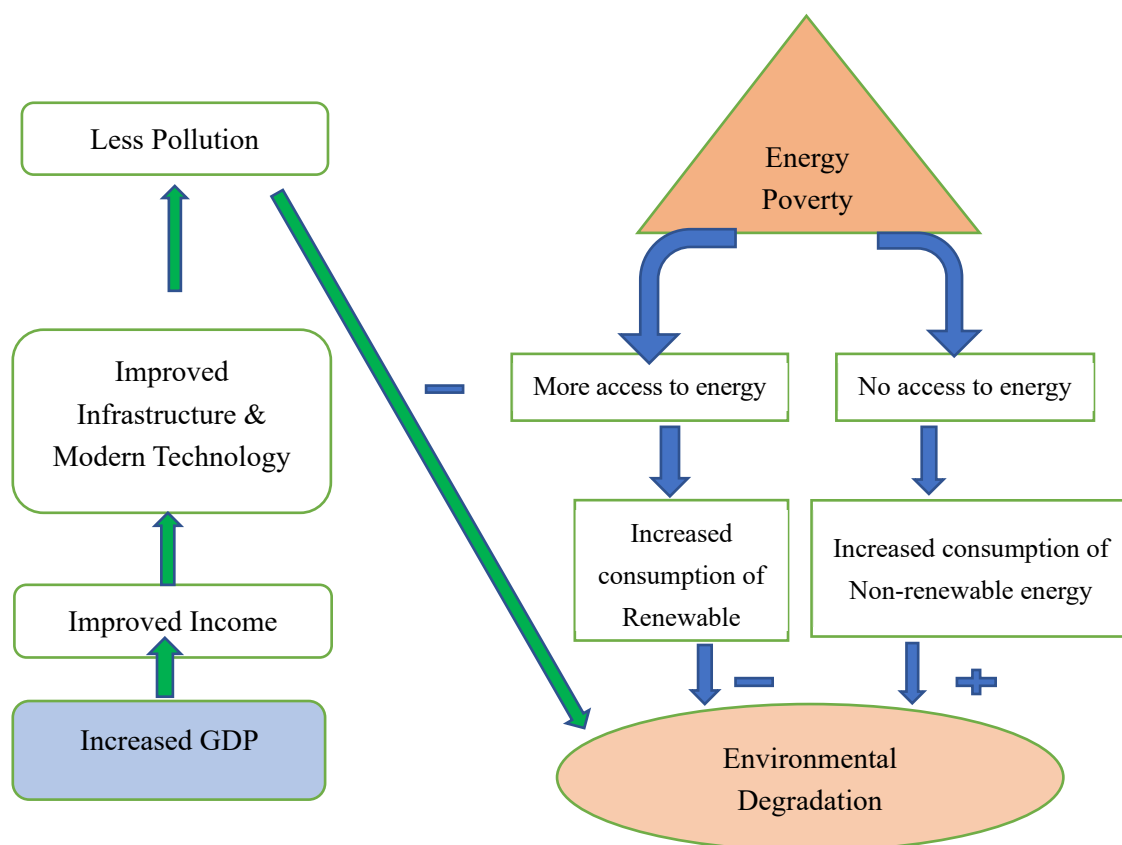
Figure 3 reveals that South Asian nations are grappling with rapid environmental degradation, mainly due to the increased use of non-renewable energy. CO<sub>2</sub> emissions have surged by 50%, with fossil fuels and natural gas accounting for over 98% of Bangladesh's primary energy sources (Our World in Data, 2024). Despite commendable government efforts, India has also reported increased CO<sub>2</sub> emissions. With its economy primarily based on agriculture, Pakistan has kept CO<sub>2</sub> emissions low. However, despite their efforts to diversify the energy mix, these nations continue to face significant environmental challenges, underscoring the crucial need for strategic energy planning.



**Figure 3.** CO<sub>2</sub> emissions in South Asian Nations.

Figure 4 shows the effects of energy poverty and economic growth on environmental degradation. Energy poverty has two dimensions: On the one hand, if energy poverty decreases, individuals will have more access to energy. They prefer to use renewable energy, which will negatively affect environmental degradation (Masron & Subramaniam, 2021). On the other hand, if energy poverty increases, individuals will have to fulfill their energy needs through nonrenewable energy consumption, ultimately damaging the environment (Masron & Subramaniam, 2021; Dimnwobi et al., 2023). The usage of coal, fuel, and wood are examples of nonrenewable energy.

On the other hand, GDP also affects environmental degradation. GDP has an inverse relationship with environmental degradation (Osuntuyi & Lean, 2022). When GDP increases, it causes increased income and improved infrastructure. Due to the use of improved infrastructure and advanced technology, less pollution is produced, which has a negative relation with environmental degradation, indicating that if there is less pollution, there will be less environmental degradation.



**Figure 4.** Possible transmission channels among the variables.

## 2.2. Theoretical literature review

In this study, we focus on the adverse environmental effects caused by energy poverty, energy resources, economic expansion, and urbanization (URB), and the following are the most relevant theories. First, the intersection of capability and environmental justice theories is the theoretical foundation for energy poverty and the environment (Schlosberg, 2012). In addition, the capability-based approach addresses several issues related to climate change, including the distribution of vulnerability, the consideration of places, people, interactions, and several fundamental rights deprivations. According to Schlosberg (2012), the framework applies adaptability to consider regional variations in climate change, as well as its consequences, experiences, and responses. According to Churchill & Smyth (2020) and Atanasiu (2014), vulnerable energy-poor families typically have low-income levels and are forced to pay high energy prices. However, there is research evidence that energy poverty is not only a financial issue but also affects the environment in general.

Energy poverty is defined as inequality and spatial justice (Simcock et al., 2017) and is associated with variables of government, environment, and society. One may argue that energy poverty violates distributive justice. Alternative energy sources like renewable energy and energy diversity can solve the problem of spatial disparity in resource allocation. Boardman (2013) suggests that energy poverty is influenced by household income, energy efficiency, and costs. Energy poverty has recently been a topic of interest, with researchers examining the link between economic growth and environmental deterioration.

Second, The Environmental Kuznets Curve (EKC) theory, developed by Dinda (2004), explains the link between GDP and environmental degradation. It depicts how environmental quality declines due to economic development and recovers (in an inverted U-shape). Grossman and Krueger (1995) identified three channels: The method effect, composition impact, and scale effect. The scale effect occurs when the economy's direction is set by economic expansion, accelerating environmental deterioration and economic expansion. Natural resources are being used more and more in production. The composition effect occurs as income increases and the industrial structure gradually changes, affecting the overall structure of the economy. Economic expansion improves environmental treatment as the secondary sector develops and cleaner technologies are adopted. This raises consumer demand for cleaner air and spurs advancements in science and industry. The third sector expands in economies with higher R&D expenditure, replacing harmful technologies with more knowledge-intensive ones, promoting economic advancement and benefiting the environment (Grossman & Krueger, 1995).

Third, Ecological modernization, compact cities, and environmental transition theories can explain the link between environmental pollution and URB. The environmental transition hypothesis suggests that URB causes increased energy usage, transportation-related activities, and infrastructure development, contributing to environmental degradation. However, URB will lower carbon emissions due to scientific discoveries, legal restrictions, and advanced energy systems (Sadorsky, 2014). The compact city theory suggests that urban institutions benefit from economies of scale for public infrastructure like transportation, power, and schools through the agglomeration effect (Ohlan, 2015). Based on theoretical and empirical evidence, the hypothesis is proposed to explain the impact of URB on environmental quality.

### *2.3. Empirical literature review*

#### **A) Environment and energy poverty**

Energy poverty and environmental pollution are significant social and economic barriers. Limited access to environmentally friendly energy resources and increasing reliance on fossil fuels in underdeveloped areas damage the environment (Vurro et al., 2022). A study by Reyes et al. (2019) established that using firewood for heating reduces the environment's quality, and energy poverty is associated with environmental degradation in the developing world (Crentsil et al., 2019). Zhao et al. (2021) established that energy poverty reduces the quality of the environment. Solving these problems is essential to successfully continue sustainable growth and minimize the negative impact on the environment.

#### **B) Environment and energy resources**

Carbon emissions and renewable and non-renewable energy resources are interrelated and affected by several factors. Renewable energy is considered the most suitable because it can be considerably less risky to the environment provided that it is utilized at the current global energy usage rate if adequately used (Ikram et al., 2020; Zaman et al., 2021). Altın et al. (2024) also examined the impact of the Carbon emissions and renewable and non-renewable energy, according to which it is revealed that the renewable energy resources are less harmful to the environment compared to the non-renewable energy sources like natural gas and oil.

Similar findings have been reported by Kuo et al. (2022) in 10 Asian nations, for 36 selected emerging countries (Omri et al., 2022), for South and East Asia (Masron & Subramaniam, 2021), and for selected Arab countries (Dimnwobi et al., 2023). However, NRE has a positive correlation with environmental degradation and causes more environmental pollution, while RE has a negative impact (Wang et al., 2016); for OPEC economies (Fakher et al., 2023) and for the G7 Countries (Voumik et al., 2023).

Our findings have significant implications for South Asian economies striving to promote sustainable energy use. By categorizing energy into non-renewable and renewable resources, the study sheds light on how these sources influence environmental sustainability in South Asia, bridging a crucial knowledge gap.

### C) Environment and economic growth

Economic growth is an essential aspect of progress. Nonetheless, the effects of economic growth on the environment have been issues to discuss globally. Economic growth is necessary to combat poverty and create the required infrastructure, but it also necessitates increased consumption of non-renewable energy sources, potentially worsening air pollution. This conflict between economic progress and environmental threats has challenged environmentalists and economists. Research has established the connection between economic growth and the release of CO<sub>2</sub>, whereby scholars claim that environmental degradation results from economic growth, especially in the early stages of development when nations are more concerned with economic growth than the environment. Some of the factors may include poor technology, poor enforcement of regulations, and low energy efficiency consciousness (Masron & Subramaniam, 2021).

Contrary to the negative narrative, economic growth has also been associated with environmental quality improvements (Rahman et al., 2021; Wang et al., 2016). This positive trend can be attributed to technological advancements, environmental awareness campaigns, diversification of energy sources, and the implementation of environmental laws (Dimnwobi et al., 2023; Voumik et al., 2023). This relationship is particularly significant in South Asian countries, as it highlights the importance of economic growth in improving environmental quality and filling the knowledge gap. We aim to address this knowledge gap and contribute to the country's environmental progress.

### D) Environment and URB

The relationship between URB, population, industrial practices, and environmental pollution has been extensively studied. Studies (James, 2024; Danish and Hassan, 2023; Wang et al., 2021; Li & Haneklaus, 2022) have shown a negative correlation between URB and environmental quality due to the transition from agriculture to industry, low energy efficiency, and high road energy use and traffic congestion. However, URB positively affects environmental quality by increasing the efficiency of public infrastructure.

Ahmad & Zhao (2018) & Wang et al. (2016) reported that a positive relationship between URB and environmental degradation exists, but Xu and Lin (2015) found no causal association. Wang et al. (2021) and Dogan and Turkekul (2016) discovered a bidirectional causal relationship. According to Shi et al. (2020), there appears to be a correlation between CO<sub>2</sub> emissions and the complexity of urban forms, leading some researchers to draw this conclusion.

We aim to contribute to the existing literature by exploring the relationship between URB and CO<sub>2</sub> emissions, which must be explored at the regional and government levels. Previous research has

examined how EP influences the characteristics of a suitable environment, particularly in South Asia. However, the results on the connection between environmental quality, EP, RE/NRE, and URB are limited, as indicated in the literature review. Thus, we aim to fill the gap by analyzing the effects of EP, RE/NRE, and URB on the environment in South Asian nations. South Asia is home to about 24%, around 1.95 billion, of the world's population (World Bank, 2024). This region is experiencing tremendous economic growth, with a growth rate of 6.4% in 2023, establishing it as the fastest-growing region (World Bank Report, 2024). Despite its economic growth, South Asia confronts enormous issues such as energy poverty and environmental deterioration. Most of the South Asian population lives off-grid and without access to clean energy (World Bank, 2024). This lack of access frequently results in reliance on nonrenewable energy sources, exacerbating environmental degradation. South Asia's rapid economic growth is notable; energy poverty and environmental degradation need further investigation for the region's long-term development. The results of this study are generalizable. Although designed to tackle the distinct socioeconomic and environmental dynamics of South Asian nations, fundamental principles such as harmonizing energy availability, economic growth, and environmental degradation can also guide policy frameworks in other regions confronting the similar challenges. However, recommendations may need to be adapted to local contexts outside South Asia.

### 3. Methodology

#### 3.1. Model construction

We utilize the EKC baseline model, which is based on previous research (Katircioglu et al., 2014; Ehigiamusoe et al., 2020; Osuntuyi & Lean, 2022) and described as follows.

$$\ln CO2_{it} = \alpha_0 + \alpha_1 \ln EP_{it} + \alpha_2 \ln GDP_{it} + \alpha_3 \ln GDP_{it}^2 + \beta_4 \ln RE_{it} + \beta_5 \ln NRE_{it} + \alpha_6 \ln URB_{it} + \epsilon_{it} \quad (1)$$

EP represents energy poverty, GDP represents real GDP per capita,  $GDP^2$  is the square of real GDP per capita, and  $CO_2$  is an environmental indicator. The EKC hypothesis is an inverted U-shape with positive GDP and negative  $GDP^2$  coefficients. The EKC hypothesis is confirmed if  $\beta_1 > 0$  and  $\beta_2 < 0$ , indicating an inverted U-shaped connection. RE represents renewable energy consumption, NRE represents non-renewable energy consumption, and URB represents URB. The error term is represented by  $\mu_{it}$ . Variables are converted into natural logarithms before analysis.

#### 3.2. Data

In this research, annual time series data of South Asian countries between 1990 and 2021, including Pakistan, India, Bangladesh, Sri Lanka, and Nepal, are used. The estimation timeframe is determined by data availability over an extended period. The variables of the study are selected because South Asia is home to about 24%, around 1.95 billion, of the world's population (World Bank, 2024). This region is experiencing tremendous economic growth, with a growth rate of 6.4% in 2023, establishing it as the fastest-growing region (World Bank Report, 2024). Despite its economic growth, South Asia nations confront enormous issues such as energy poverty and environmental deterioration. The majority of the South Asian population lives off-grid and without access to clean energy (Bank, 2024). This lack of access results in reliance on nonrenewable energy sources, exacerbating

environmental degradation. The rapidly economic growth in South Asia region is notable; energy poverty and environmental degradation need further investigation for long-term development.

The key variable, energy poverty means the lack of access to adequate, affordable, reliable, and clean energy services. This condition affects billions worldwide, hindering economic development, health outcomes, and overall quality of life. The MIT Energy Initiative (2024) defines energy poverty as spending over 6% of household income on energy. This situation is exacerbated by climate change, leading to increased energy consumption for air conditioning and higher burdens on low-income households.

Further, environmental degradation is a process of degradation of the environment, including lack of resources, destruction of the ecosystem, and pollution resulting from human activities that have a bad impact on the environment and human beings (Maurya et al., 2020).

**Table 1.** Variable descriptions and data sources.

| Variables                    | Abbreviations   | Unit of Measurement                 | Description                                                                                                                  | Sources     |
|------------------------------|-----------------|-------------------------------------|------------------------------------------------------------------------------------------------------------------------------|-------------|
| CO <sub>2</sub> emissions    | CO <sup>2</sup> | Metric tons per capita              | Carbon dioxide emissions are produced from the consumption of solid, liquid, gas flaring, and gas fuels.                     | WDI (2022). |
| Energy poverty               | EP              | % of Population                     | The percentage of the population without access to energy is known as “energy poverty.”                                      | WDI (2022). |
| GDP growth                   | GDP             | Annual %                            | GDP is calculated as the total gross value of goods created within a year by all producers who are residents of the economy. | WDI (2022). |
| Renewable energy consumption | RE              | % of Total Final Energy Consumption | The share of renewable energy in all final energy consumption is known as “renewable energy consumption.”                    | WDI (2022). |
| Non-Renewable energy         | NRE             | % of Total                          | Energy production is done with the help of coal sources, oil, and gas.                                                       | EIA (2021)  |
| Population growth            | POP             | Annual %                            | The annual percentage change in the population of a particular area, region, or county during a specific time.               | WDI (2022). |

### 3.3. Estimation strategy

#### 3.3.1. Cross-sectional dependency tests

Examining cross-sectional dependency between nations is essential to analyzing panel data, as a shock in one can affect others (Destek & Aslan, 2020). The cross-sectional dependency test, which is used to avoid biased and inconsistent estimations is based on three tests: Breusch-Pagan Lagrange multiplier (LM) (Breusch & Pagan, 1980), Pesaran scaled LM, and Pesaran cross-sectional dependency (CD) (Pesaran & Smith, 1995). Table 3 demonstrates no cross-sectional dependency between these three tests, indicating that the null hypothesis is rejected.

#### 3.3.2. Panel stationarity test results

Understanding the time-series properties of the data is crucial to prevent spurious regression. Pesaran (2007) developed different panel unit root tests to determine the stationarity and integration order of the model’s variables. To determine long-term associations, we must first confirm the

stationarity of the presented variables. This investigation begins with panel unit root tests, as shown in Table 4. The unit root tests include the Levin, Lin, and Chu (LLC) test (Levin et al., 2002), the Im, Pesaran, and Shin (IPS) test (Im et al., 2003), and Fisher-type tests utilizing Augmented Dickey-Fuller (ADF) unit roots.

### 3.3.3. Panel cointegration test results

The Westerlund (2007) test operates on structural rather than residual dynamics, thereby avoiding the imposition of any common-factor restriction. This test considers cross-section dependencies and accommodates non-strictly exogenous regressors. It addresses nuisances arising from the endogeneity of regressors and exhibits substantial statistical power compared to cointegration based on dynamic tests (Altıntaş & Kassouri, 2020). Table 5 presents the outcomes of the cross-sectional dependency co-integration test on the Westerlund panel, revealing significant long-run relationships between the variables.

### 3.4. Panel long-run estimators

The Pooled Mean Group (PMG) estimator provides an exclusive constraint on long-term coefficients, enabling short-term coefficients, intercepts, and adjustment speeds to vary between countries. This makes the PMG estimator appropriate when long-term trends are believed to be consistent worldwide (Pesaran et al., 1999). Certain countries, however, may be distinct due to geographic, climatic, institutional, economic, and macroeconomic policies, resulting in significant but variable short-term effects. In these cases, the PMG estimator is favored. PMG evaluation can provide insights into both short-term and long-term outcomes, giving policymakers various options for decision-making.

For robustness checks, Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimations are employed, consistent with studies in the literature (Dogan et al., 2019; Mesagan, 2022; Munir et al., 2020). Pedroni proposed the FMOLS heterogeneous panel cointegration approach. The FMOLS is a nonparametric method (Bayale et al., 2021; Ulucak and Khan, 2020) that addresses endogeneity and autocorrelations (Shahbaz et al., 2017), correcting simultaneous bias and serial correlation. It also considers intercept-related problems and removes biases and homogeneity constraints associated with missing data (Raza & Shah, 2018).

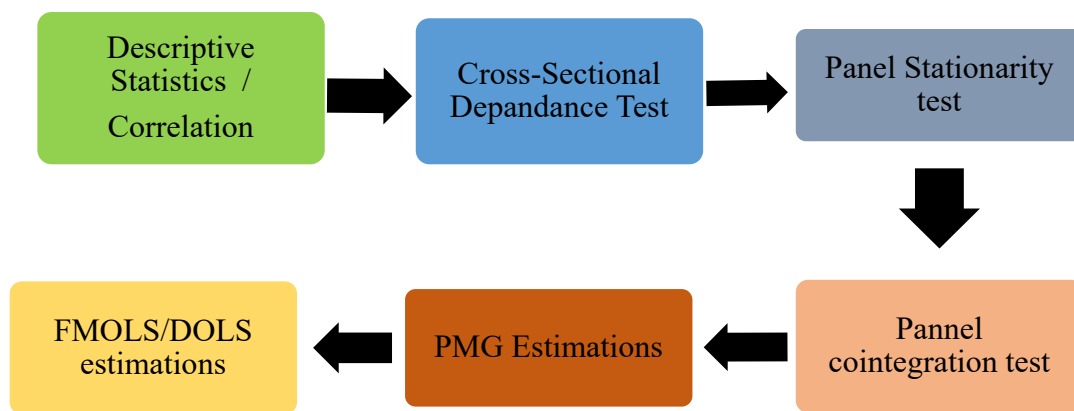
However, the DOLS method is based on a parametric dynamic panel created by Kao and Chiang (Kao & Chiang, 2000). It solves endogeneity, serial correlation, and simultaneity problems. It produces objective long-term estimates, adds contemporaneous values of lags and regressors, and transforms a static regression into a first-difference specification (Bayale, 2021). It also exhibits resilience and asymptotic efficiency in limited samples. These methods are used because they produce robust estimates that consider the panel dataset's dynamics. By resolving potential endogeneity problems, we provide findings and robustness outcomes in the longer-term correlations between these variables. Also, using FMOLS and DOLS techniques can increase the credibility and accessibility of the findings by ensuring that our models are consistent with our objectives.

Equations (2) and (3) represent the FMOLS and DOLS estimators, where  $X$  and  $Y$  are independent and dependent variable(s) respectively.

$$\hat{\beta}_{FMOLS} = \frac{1}{N} \sum_{i=1}^N \left[ \left( \sum_{t=1}^T (X_{it} - \bar{X}_i)^2 \right)^{-1} x \left( \sum_{t=1}^T (X_{it} - \bar{X}_i) \hat{Y}_{1t} - T \hat{\Delta}_{\epsilon\mu} \right) \right] \quad (2)$$

$$\hat{\beta}_{DOLS} = \frac{1}{N} \sum_{i=1}^N \left[ \left( \sum_{t=1}^T (X_{it} - \bar{X}_{it})^2 \right)^{-1} x \left( \sum_{t=1}^T X_{it} \hat{Y}_{it} \right) \right] \quad (3)$$

Figure 5 depicts the study's methodological structure. The variance inflation factor (VIF) is used to identify possible multicollinearity, with VIF values less than ten indicating non-existence (Gujarati & Porter, 2009). The Wooldridge and Breusch–Pagan/Cook–Weisberg tests are also performed. The findings demonstrate that serial correlation and heteroskedasticity are present.



**Figure 5.** The methodological framework.

## 4. Results and discussion

### 4.1. Preliminary analysis

Table 2 presents the descriptive statistics and the correlation matrix of the variables applied in this study's estimations. The standard deviation reflects the degree of dispersion from the mean value for each variable (Osuntuyi & Lean, 2022). Notably, the nonrenewable energy consumption variable exhibits the highest standard deviation among all the variables considered. The correlation coefficients displayed in the lower panel of the table indicate that positive relationships exist among the variables. For instance, the positive correlation between energy poverty and environmental degradation is moderate, while the negative correlation between renewable energy consumption and environmental degradation is weak. This suggests that increasing renewable energy consumption may have a limited impact on reducing environmental degradation, while addressing energy poverty could have a more significant effect.

**Table 2.** Descriptive statistics and correlation analysis.

|                    | lnCO <sub>2</sub> | lnEP   | lnGDP  | LnRN   | lnNRN | lnURB |
|--------------------|-------------------|--------|--------|--------|-------|-------|
| Mean               | 0.955             | 4.026  | 1.542  | 4.051  | 6.815 | 4.051 |
| Std. dev.          | 0.890             | 0.510  | 0.537  | 0.287  | 2.323 | 0.350 |
| Min                | 0.500             | 2.293  | 2.119  | 3.424  | 1.230 | 3.424 |
| Max                | 3.005             | 4.601  | 2.213  | 4.555  | 7.608 | 4.555 |
| Correlation matrix |                   |        |        |        |       |       |
| lnCO <sub>2</sub>  | 1.000             |        |        |        |       |       |
| lnEP               | 0.713             | 1.000  |        |        |       |       |
| lnGDP              | 0.152             | 0.737  | 1.000  |        |       |       |
| lnRN               | -0.764            | -0.462 | -0.256 | 1.000  |       |       |
| lnNRN              | 0.752             | -0.458 | -0.259 | -0.999 | 1.000 |       |
| lnURB              | 0.722             | -0.502 | -0.117 | 0.035  | 0.022 | 1.000 |

#### 4.2. Cross-sectional dependence test results

The first part of Table 3 displays cross-sectional dependence among panel variables using the Breusch-Pagan LM test, Pesaran scaled LM test, and Pesaran CD test. At a 1% significance level, the findings reject the null hypothesis of no cross-sectional dependence, demonstrating that shocks in one nation can affect others in the panel. This implies that policies or events in one South Asian country could have spillover effects on the environmental conditions of other countries in the region, highlighting the need for coordinated regional environmental policies.

Furthermore, the second part of Table 3 applies the Westerlund cointegration to various models based on energy poverty variables by geographical area and overall. The test results confirm cointegration at a 1% significant level, indicating the existence of long-term relationships between the study's variables. Cointegration suggests that the variables move together in the long run, implying that changes in one variable, such as energy poverty, can have lasting effects on other variables, such as environmental degradation, and vice versa.

**Table 3.** Cross-sectional dependence and panel cointegration test results.

| Dependent Variables             | lnCO <sub>2</sub> |
|---------------------------------|-------------------|
| Breusch Pagan LM                | 86.04963***       |
| Pesaran Scaled LM               | 17.0052***        |
| Pesaran CD                      | 3.7930***         |
| Panel Cointegration Results     |                   |
| Model with Total Energy Poverty | -2.8126***        |

Notes: \*\*\* indicates statistically significant at 1%.

#### 4.3. Panel stationarity test results

Table 4 presents the results of panel unit root tests, including the IPS test (Im et al., 2003), the ADF-Fisher test (Maddala & Wu., 1999), and the LLC test (Levin et al., 2002). Our results show that some variables exhibit stationarity at the level, but other variables are stationary at first difference.

**Table 4.** Panel stationarity test results.

|                   | ADF- Fisher<br>Chi-square | Levin, Lin & Chu | Im, Pesaran and<br>Shin |
|-------------------|---------------------------|------------------|-------------------------|
| Level             |                           |                  |                         |
| Variables         |                           |                  |                         |
| lnCO <sub>2</sub> | 24.040***                 | -2.294**         | -2.295**                |
| LnEP              | 283.499***                | -11.482***       | -8.621***               |
| LnGDP             | 791.645***                | -17.715**        | -25.315***              |
| LnRN              | 3.986*                    | 0.938            | 2.113                   |
| LnNRN             | 16.210*                   | -0.551           | -1.364                  |
| LnURB             | 17.645*                   | -0.179           | -1.213                  |
| First Difference  |                           |                  |                         |
| lnCO <sub>2</sub> | 61.497***                 | -5.9541***       | -7.236***               |
| LnEP              | 357.104***                | -6.2159***       | -15.843***              |
| LnGDP             | 790.737***                | -32.3842***      | -33.625***              |
| LnRN              | 57.235***                 | -6.1123***       | -7.049***               |
| LnNRN             | 64.227***                 | -5.5614***       | -7.332***               |
| LnURB             | 50.790***                 | -7.7002***       | -6.002**                |

Notes: \*\*\*, \*\*, and \* indicate statistically significant values at 1%, 5%, and 10%, respectively.

#### 4.4. Diagnostic tests

One of the most valuable statistics to assess multicollinearity in a model is the variance inflation factor (VIF); it is considered that the VIF is less than 10, indicating the absence of multicollinearity (Gujarati & Porter, 2009). To test for heteroskedasticity in the model, the Breusch-Pagan/Cook-Weisberg test and the Wooldridge test are used for serial correlation. It is seen that there is no serial correlation or heteroskedasticity in the results, and the panel unit root tests suggest the use of the PMG estimator for the study. The FMOLS and DOLS approaches are utilized for robustness checks. We also look at the relationship between the variables of interest over time: Energy poverty, consumption of energy resources, economic growth, URB, and environmental pollution. Our findings are summarized in Table 5.

The study reveals that in models 1–3, the coefficient of energy poverty is positive and statistically significant at 1% levels in PMG and FMOLS, while at 5% level in the DOLS, suggesting that energy poverty fluctuations can explain the deterioration of the environment in the South Asian countries. The findings are that energy poverty leads to environmental pollution, hence environmental degradation in South Asia. According to the PMG, FMOLS, and DOLS estimations, a 1% increase in EP leads to the pollution levels of 0.217%, 0.271%, and 0.289% respectively. This result is consistent with research by Katircioglu et al. (2014), who found that environmental degradation is a result of energy poverty. However, this finding contradicts earlier research (Haleem et al., 2020; Doğanalp et al., 2021) showing that energy poverty reduces environmental pollution.

**Table 5.** Impacts of energy poverty and economic growth on the environment.

| Variables                    | (1)<br>PMG            | (2)<br>FMOLS           | (3)<br>DOLS           |
|------------------------------|-----------------------|------------------------|-----------------------|
| Long run                     |                       |                        |                       |
| lnEP                         | 0.217***<br>(2.543)   | 0.271***<br>(2.945)    | 0.289**<br>(2.477)    |
| lnGDP                        | 0.031***<br>(2.253)   | 0.026<br>(0.386)       | 0.414***<br>(2.76)    |
| lnGDP <sup>2</sup>           | 0.342<br>(1.710)      | 0.306***<br>(8.541)    | -0.098<br>(-0.494)    |
| lnRN                         | -1.000***<br>(-9.581) | -1.266***<br>(-40.398) | -2.251***<br>(-9.075) |
| lnNRN                        | 0.006***<br>(3.338)   | 0.221**<br>(3.210)     | 1.073***<br>(5.224)   |
| lnURB                        | 0.358***<br>(5.158)   | 0.075**<br>(2.081)     | 0.219***<br>(3.013)   |
| Short run                    |                       |                        |                       |
| ECT (-1)                     | -0.646***<br>(-3.304) |                        |                       |
| $\Delta(\ln\text{CO}_2)(-1)$ | -0.131<br>(-0.987)    |                        |                       |
| $\Delta(\ln\text{CO}_2)(-2)$ | 0.149<br>(0.986)      |                        |                       |
| $\Delta(\ln\text{EP})$       | 0.379<br>(1.708)      |                        |                       |
| $\Delta(\ln\text{GDP})$      | 0.039<br>(1.737)      |                        |                       |
| $\Delta(\ln\text{GDP}^2)$    | 0.138<br>(0.192)      |                        |                       |
| $\Delta(\ln\text{RN})$       | 0.637<br>(1.807)      |                        |                       |
| $\Delta(\ln\text{NRN})$      | 0.008<br>(1.703)      |                        |                       |
| $\Delta(\ln\text{URB})$      | 0.246<br>(1.616)      |                        |                       |
| Mean VIF                     | 1.65                  |                        |                       |
| Heteroskedasticity           | 3.88<br>(0.048)       |                        |                       |
| Serial Correlation           | 94.795<br>(0.000)     |                        |                       |

Notes: \*\*\*, \*\*, and \* indicate statistically significant values at 1%, 5%, and 10%, respectively.

Innovative technology and smart grids in energy utilization can reduce nonrenewable energy consumption and reduce the exploitation of natural resources. In addition, proper waste management and new technologies in waste disposal through energy recycling will help reduce waste disposed of in lowlands and help cut the costs of water and land pollution. Advanced transport solutions, such as electric cars and other fuels, improve air quality and CO<sub>2</sub> emissions. Thus, reducing energy poverty can help protect the environment by reducing the impacts of climate change in South Asian countries.

As for economic growth, the results show that the coefficient of GDP and CO<sub>2</sub> is significantly positive in the FMOLS and DOLS methods. They prove that any rise in GDP, even by 1%, will increase pollution by 0.25% in the long run. These findings support the studies by Al-Mulali et al. (2015), Jie et al. (2023), and Munir et al. (2020). Moreover, the results advocate that South Asia's pursuit of economic expansion may have ignored environmental protection. These observations can be linked to

the beginning of time due to this long-standing trade-off. One of the major issues is that South Asia depends on fossil resources; thus, the economic growth rates may need to be revised. In addition, economic growth has led to environmental degradation in South Asian countries mainly because of industrialization. The high economic growth rate and the integration of the region's economy into the global economy have led to more industrialization and, hence, more pollution. Additionally, the production and consumption of services and goods have contributed to the creation of waste and pollution of land, air, and water resources.

However, the findings concerning the squared term are intriguing in this study. The positive result with PMG and FMOLS negates the EKC hypothesis and disproves the EKC theory, indicating that it is unrealistic in South Asia's energy-poor region. This means that there are no remedies to the effects of economic expansion if there is no provision for clean and convenient energy. The results also align with the fact that EKC does not exist in South Asian countries due to its excessive reliance on fossil fuels. These nations should also focus on economic growth at the cost of environmental stability. However, due to its climate change threats in this region, South Asian nations encounter increased environmental pressures because of its emergence as a leading global manufacturer. This emphasizes the need for South Asia to develop energy investment policies that will not be detrimental to the environment. This has important implications for South Asia's energy policies and shows that this region has to rely on clean, comfortable energy sources to offset the adverse effects of expanding the region's economy on the environment.

We found that renewable energy consumption in South Asia is negative and statistically significant. This suggests that increasing the use of renewable energy can decrease CO<sub>2</sub> emissions in South Asian countries, contributing to global efforts to combat climate change. These results are consistent with other studies (Wang et al., 2016; Zaman et al. 2021). The region's economic expansion and dense population have increased energy demand, which is now fulfilled primarily by fossil fuels. However, burning fossil fuels causes pollution in the air and greenhouse gases, further degrading the environment. In contrast, renewable energy sources such as hydro, wind, solar, and biomass provide a long-term substitute for fossil fuels (Dimnwobi et al., 2023). Adopting and utilizing these technologies can decrease reliance on fossil fuels, increase energy security, and reduce GHG emissions. Furthermore, renewable energy sources can deliver electricity to rural areas, contributing to economic growth and enhancing their life quality. However, it is essential to note that sustainable renewable energy projects must be implemented to lessen negative environmental impacts like habitat loss and fragmentation. Moreover, encouraging and promoting renewable energy use in South Asia can significantly decrease the amount of CO<sub>2</sub> and contribute to sustainable development goals.

Despite non-renewable energy consumption effects on CO<sub>2</sub> levels in South Asia, their excessive use and mishandling have had detrimental implications, emphasizing the necessity for sustainable practices and appropriate measures. It has a statistically significant and positive effect on pollution. The overuse of underground water resources for industry and farming has depleted and contaminated aquifers, resulting in water shortages and pollution. Over-exploitation of forests' resources for wood and other forest-based goods and cutting forests for URB and farming has caused habitat loss, reduced biodiversity, and enhanced carbon emissions. Another reason for increased pollution in the region is the mining of coal and oil resources. Furthermore, NRN contributes to CO<sub>2</sub> emissions and reduces the region's ecological excellence. This finding is similar to other research (Nong et al., 2021 and Fatima et al. 2021). South Asia's growing use of non-renewable energy, such as coal, natural gas,

and oil, accounts for over 85% of total energy consumption and contributes to rising CO<sub>2</sub> emissions (Khan & Gunwant, 2024).

URB has also contributed to environmental pollution, deforestation, and the effects of climate change, which are destructive to the natural environment. The transportation system for transferring people and products has also increased CO<sub>2</sub> emissions, contributing to the climate crisis. For instance, a 1% increase in URB is associated with a rise in environmental pressures of 0.358%, 0.075%, and 0.219% as estimated by the PMG, FMOLS, and DOLS models, respectively. This finding is consistent with research by Azam & Khan (2016), and Ren (2015).

Therefore, the South Asian URB is essential for the sustainable development of the environment, economy, and society, which should be managed in the region. Nonetheless, Li and Haneklaus (2022), and Wang et al. (2021) established a negative association between URB and environmental quality, resulting in the shift from agricultural to industrial and poor infrastructure, such as traffic jams and energy density. Some countries need to implement sustainable environmental policies, which has worsened the negative environmental impacts. The above effects show the need for sustainable policies, action plans, and immediate implementation to address the above.

The SIC is used to determine the maximum lag length of 3 in Model 1, which shows the cointegration relationship between energy poverty and environmental degradation. This is further supported by the negative signs and statistical significance of the convergence coefficient, which reflects the speed at which the system returns to equilibrium after a short period of shock (Pesaran et al., 1999). For instance, if the economy is shifted in the short run, it will require 1.5 years to return to the long-run equilibrium. This means the economy will gradually return to its stable, long-term growth path after a temporary shock. The PMG model's adjustment speed is 64%, and the total adjustment happens at 100%. However, the association between energy poverty, economic growth, and the environment is not statistically significant in the short term.

## 5. Conclusion and policy implications

Pollution has significantly impacted the ecosystem, causing considerable deterioration in the global environment. While factors influencing the environment have been studied, more research is needed on the effects of energy poverty on environmental contamination in South Asian countries. Hence, we aimed to investigate the direct effects of energy poverty and economic growth on environmental degradation in the selected South Asian countries from 1990 to 2021 based on the EKC hypothesis. Furthermore, we employed empirical methods to address the challenges of endogeneity, heterogeneity, and cross-sectional dependence, particularly in comparing energy resources.

We began with a comprehensive exploratory analysis of the available empirical data, ensuring a robust foundation for the research. CSD tests on panel variables, including the Breusch-Pagan LM test, the Pesaran scaled LM test, and the Pesaran CD test, revealed cross-sectional dependence among panel countries, implying that any shock in one country may influence others. The IPS, ADF, and LLC tests were used to investigate the variables' integration order. The Westerlund cointegration method was employed to assess the cointegration relationships between variables used in the study. Long-run findings were derived through the PMG method, and robustness tests using FMOLS and DOLS were conducted, with diagnostic tests employed to confirm results.

The study's estimation techniques revealed that energy poverty positively relates to environmental degradation. The lack of access to modern energy in South Asia forces people to use

non-renewable energy resources, which causes environmental pollution and significant environmental degradation. However, renewable energy use in South Asia negatively relates to environmental degradation, indicating that renewable energy causes less harm to the environment.

Additionally, the study revealed that increasing economic growth increases South Asian pollution. The Environmental Kuznets Curve was not present in South Asian countries, meaning that the GDP of South Asian countries alone is insufficient to eliminate CO<sub>2</sub> emissions from economic growth. However, there is potential for renewable energy to reduce CO<sub>2</sub> emissions. Based on our findings, the economy will take 1.5 years to converge back to a long-run equilibrium in the event of a short-run deviation. The Intergovernmental Panel on Climate Change (IPCC) recommends that South Asian nations use fewer fossil fuels and more renewable energy sources to lessen environmental degradation. Investing in green infrastructure and eco-friendly technologies is also recommended.

We recommend that governments proactively promote renewable energy use and switch to renewable energy sources like solar, wind, and hydropower to reduce dependence on coal and biomass. This can help lower pollution and address energy poverty. The government can achieve this by strengthening renewable energy policies, providing off-grid energy solutions, offering soft loans, and lowering taxes. By promoting innovative development technologies and green urban development through boosting investment, promoting renewable energy usage, and offering affordable equipment and technology, governments can empower their citizens to make sustainable choices.

Furthermore, the study underscores the urgent need for South Asia to prioritize measures that reduce energy poverty, promote economic growth, and address environmental issues. It also suggests that South Asia avoids implementing energy, financial, and environment-related policies that may have conservative effects on energy, growth, and the environment. In conclusion, there is a pressing need to create policies that lessen energy poverty, promote economic growth, and solve environmental issues, as these are crucial for the region's sustainable development.

### **Author contributions**

Memona Rasheed: Conceptualization; Data curation; Methodology; Formal analysis; Writing - original draft; Hooi Hooi Lean: Conceptualization; Writing - review and editing; Resources; Supervision; Visualization; Nam Foo: Validation; Writing - review and editing.

### **Use of AI tools declaration**

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

### **Conflict of interest**

The authors declare no conflict of interest.

### **References**

Ahmad M, Zhao ZY (2018) Empirics on linkages among industrialization, urbanization, energy consumption, CO<sub>2</sub> emissions and economic growth: a heterogeneous panel study of China. *Environ Sci Pollut Res* 25: 30617–30632. <https://doi.org/10.1007/s11356-018-3054-3>

- Altın H (2024) The impact of energy efficiency and renewable energy consumption on carbon emissions in G7 countries. *Int J Sustain Eng* 17: 134–142. <https://doi.org/10.1080/19397038.2024.2319648>
- Al-Mulali U, Saboori B, Ozturk I (2015) Investigating the environmental Kuznets curve hypothesis in Vietnam. *Energy Policy* 76: 123–131. <https://doi.org/10.1016/j.enpol.2014.11.019>
- Altıntaş H, Kassouri Y (2020) Is the environmental Kuznets Curve in Europe related to the per-capita ecological footprint or CO<sub>2</sub> emissions? *Ecol Indic* 113: 106187. <https://doi.org/10.1016/j.ecolind.2020.106187>
- Atanasiu B (2014) The role of energy efficiency in addressing energy poverty. *European Commission Workshop Report*.
- Azam M, Khan AQ (2016) Urbanization and Environmental Degradation Evidence from Four SAARC Countries. *Environ Prog Sustain Energy* 35: 823–832. <https://doi.org/10.1002/ep.12282>
- Bayale N, Ali E, Tehagnao AF, et al. (2021) Determinants of renewable energy production in WAEMU countries: new empirical insights and policy implications. *Int J Green Energy* 18: 602–614. <https://doi.org/10.1080/15435075.2021.1875467>
- Boardman B (2013) Challenges and Solutions, *Fixing Fuel Poverty*. Routledge. <https://doi.org/10.4324/9781849774482>
- Churchill SA, Smyth R (2020) Energy poverty and health: Panel data evidence from Australia. *Energy Econ* 86: 104627. <https://doi.org/10.1016/j.eneco.2021.105219>
- Crentsil AO, Asuman D, Fenny AP (2019) Assessing the determinants and drivers of multidimensional energy poverty in Ghana. *Energ Policy* 133: 110884. <https://doi.org/10.1016/j.enpol.2019.110884>
- Danish M, Hassan ST (2023) Investigating the interaction effect of urbanization and natural resources on environmental sustainability in Pakistan. *Int J Environ Sci Technol* 20: 8477–8484. <https://doi.org/10.1007/s13762-022-04497-x>
- Destek MA, Aslan A (2020) Disaggregated renewable energy consumption and environmental pollution nexus in G-7 countries. *Renew Energ* 151: 1298–1306. <https://doi.org/10.1016/j.renene.2019.11.138>
- Dimnwobi SK, Okere KI, Onuoha FC, et al. (2023) Energy poverty, environmental degradation and agricultural productivity in Sub-Saharan Africa. *Int J Sustain Dev World Ecol* 30: 428–444. <https://doi.org/10.1080/13504509.2022.2158957>
- Dinda S (2004) Environmental Kuznets curve hypothesis: a survey. *Ecol Econ* 49: 431–455. <https://doi.org/10.1016/j.ecolecon.2004.02.011>
- Dogan E, Turkecul B (2016) CO<sub>2</sub> emissions, real output, energy consumption, trade, urbanization, and financial development: testing the EKC hypothesis for the USA. *Environ Sci Pollut Res* 23: 1203–1213. <https://doi.org/10.1007/s11356-015-5323-8>
- Dogan E, Taspinar N, Gokmenoglu KK (2019) Determinants of Ecological Footprint in MINT countries. *Energy Environ* 30: 1065–1086. <https://doi.org/10.1177/0958305X19834279>
- Doğanalp N, Ozsolak B, Aslan A (2021) The effects of energy poverty on economic growth: a panel data analysis for BRICS countries. *Environ Sci Pollut Res* 28: 50167–50178. <https://doi.org/10.1007/s11356-021-14185-x>
- Ehigiamusoe KU, Lean HH, Chan JH (2020) The Influence of Macroeconomic Stability on Financial Development in Developing Economies: Evidence from the West African Region. *Singap Econ Rev* 65: 837–856. <https://doi.org/10.1142/S0217590819500553>
- Fakher HA, Ahmed Z, Acheampong AO, et al. (2023) Renewable energy, nonrenewable energy & environmental quality nexus: an investigation of the N-shaped Environmental Kuznets Curve based on six environmental indicators. *Energy* 263: 125660. <https://doi.org/10.1016/j.energy.2022.125660>

- Fatima T, Shahzad U, Cui L (2021) Renewable and nonrenewable energy consumption, trade and CO<sub>2</sub> emissions in high emitter countries: does the income level matter? *J Environ Plan Manag* 64: 1227–1251. <https://doi.org/10.1080/09640568.2020.1816532>
- Grossman GM, Krueger AB (1995) Economic growth and the environment. *Q J Econ* 110: 353–377. <https://doi.org/10.2307/2118443>
- Gujarati DN, Porter DC (2009) *Basic Econometrics. 5th ed. McGraw-Hill International Edition*, New York, NY, USA.
- Haleem A, Khan M, Athar F (2020) Energy poverty and its impact on environment: a case study of Pakistan. *J Econ Manag Sci* 1: 68–89.
- Ikram M, Zhang Q, Sroufe R, et al. (2020) Towards a sustainable environment: the nexus between ISO 14001, renewable energy consumption, access to electricity, agriculture and CO<sub>2</sub> emissions in SAARC countries. *Sustain Prod Consum* 22: 218–230. <https://doi.org/10.1016/j.spc.2020.03.011>
- Im KS, Pesaran MH, Shin Y (2003) Testing for unit roots in heterogeneous panels. *J Econometrics* 115: 53–74. [https://doi.org/10.1016/S0304-4076\(03\)00092-7](https://doi.org/10.1016/S0304-4076(03)00092-7)
- James N (2024) Urbanization and its impact on environmental sustainability. *J Appl Geogr Stud* 3: 54–66. <https://doi.org/10.47941/jags.1624>
- Jie H, Zaman S, Zaman QU, et al. (2023) A pathway to a sustainable future: Investigating the contribution of technological innovations, clean energy, and Women's empowerment in mitigating global environmental challenges. *J Clean Prod* 421: 138499. <https://doi.org/10.1016/j.jclepro.2023.138499>
- Kao C, Chiang MH (2000) On the estimation and inference of a cointegrated regression in panel data. *Adv Econometrics* 15:179–222. [https://doi.org/10.1016/S0731-9053\(00\)15007-8](https://doi.org/10.1016/S0731-9053(00)15007-8)
- Katircioglu ST (2014) Testing the tourism-induced EKC hypothesis: the case of Singapore. *Econ Model* 41: 383–391. <https://doi.org/10.1016/j.econmod.2014.05.028>
- Khan I, Gunwant DF (2024) An impact analysis of macroeconomic factors on South Asia's renewable energy output. *Int J Energy Sect Manag* 18: 539–558. <https://doi.org/10.1108/IJESM-01-2023-0013>
- Kuo Y, Maneengam A, Phan TC, et al. (2022) Fresh evidence on environmental quality measures using natural resources, renewable energy, non-renewable energy and economic growth for 10 Asian nations from CS-ARDL technique. *Fuel* 320: 123914. <https://doi.org/10.1016/j.fuel.2022.123914>
- Levin A, Lin CF, Chu CSJ (2002) Unit root tests in panel data: asymptotic and finite sample properties. *J Econometrics* 108: 1–24. [https://doi.org/10.1016/S0304-4076\(01\)00098-7](https://doi.org/10.1016/S0304-4076(01)00098-7)
- Li B, Haneklaus N (2022) Reducing CO<sub>2</sub> emissions in G7 countries: the role of clean energy consumption, trade openness, and urbanization. *Energy Rep* 8: 704–713. <https://doi.org/10.1016/j.egyr.2022.01.238>
- Maddala GS, Wu S (1999) A Comparative Study of Unit Root Tests with Panel Data and a New Simple Test. *Oxford B Econ Stat* 61: 631–652. <http://dx.doi.org/10.1111/1468-0084.61.s1.13>
- Masron TA, Subramaniam Y (2021) Renewable energy and poverty–environment nexus in developing countries. *Geo J* 86: 2099–2115. <https://doi.org/10.1007/s10708-019-10073-7>
- Maurya PK, Ali SA, Ahmad A, et al. (2020) An introduction to environmental degradation: Causes, consequence and mitigation. *Environ Degrad Causes Remediat Strateg*, 1–20. <https://doi.org/10.26832/aesa-2020-edcrs-01>
- Mesagan EP (2022) Environmental sustainability in Sub-Saharan Africa: the case of production and consumption activities. *J Knowl Econ* 13: 2840–2867. <https://doi.org/10.1007/s13132-021-00842-6>
- Munir Q, Lean HH, Smyth R (2020) CO<sub>2</sub> emissions, energy consumption and economic growth in the ASEAN-5 countries: A cross-sectional dependence approach. *Energy Econ* 85: 104571. <https://doi.org/10.1016/j.eneco.2019.104571>

- Nathaniel SP, Adeleye N (2021) Environmental preservation amidst carbon emissions, energy consumption, and urbanization in selected African countries: implication for sustainability. *J Clean Prod* 285: 125409. <https://doi.org/10.1016/j.jclepro.2020.125409>
- Nong D, Simshauser P, Nguyen DB (2021) Greenhouse gas emissions CO<sub>2</sub> emissions: Comparative analysis of a global carbon tax. *Applied Energy* 298: 117223. <https://doi.org/10.1016/j.apenergy.2021.117223>
- Ohlan R (2015) The impact of urbanization and energy consumption on CO<sub>2</sub> emissions in India. *Environ Dev* 13: 1–11. <https://doi.org/10.1016/j.envdev.2014.11.002>
- Omri A, Saidi K (2022) Factors influencing CO<sub>2</sub> emissions in the MENA countries: the roles of renewable and non-renewable energy. *Environ Sci Pollut Res* 29: 1–12. <https://doi.org/10.1007/s11356-022-19727-5>
- Osuntuyi BV, Lean HH (2022) Economic growth, energy consumption and environmental degradation nexus in heterogeneous countries: Does education matter? *Environ Sci Eur* 34: 48. <https://doi.org/10.1186/s12302-022-00624-0>
- Pedroni P (2022) Fully modified OLS for heterogeneous cointegrated panels. *Nonstationary panels, panel cointegration, and dynamic panels*. Emerald Group Publishing Limited, 15: 93–130. [https://doi.org/10.1016/S0731-9053\(00\)15004-2](https://doi.org/10.1016/S0731-9053(00)15004-2)
- Pesaran MH, Smith R (1995) Estimating long-run relationships from dynamic heterogeneous panels. *J Econometrics* 68: 79–113. [https://doi.org/10.1016/0304-4076\(94\)01644-F](https://doi.org/10.1016/0304-4076(94)01644-F)
- Pesaran MH, Shin Y, Smith RP (1999) Pooled mean group estimation of dynamic heterogeneous panels. *J Am Stat Assoc* 94: 621–634. <https://doi.org/10.2307/2670182>
- Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. *J Appl Econom* 22: 265–312. <https://doi.org/10.1002/jae.951>
- Rahman MM, Nepal R, Alam K (2021) Impacts of human capital, exports, economic growth and energy consumption on CO<sub>2</sub> emissions of a cross-sectionally dependent panel: evidence from the newly industrialized countries (NICs). *Environ Sci Policy* 121: 24–36. <https://doi.org/10.1016/j.envsci.2021.03.017>
- Raza SA, Shah N (2018) Testing environmental Kuznets curve hypothesis in G7 countries: The role of renewable energy consumption and trade. *Environ Sci Pollut Res* 25: 26965–26977. <https://doi.org/10.1007/s11356-018-2673-z>
- Ren G (2015) Urbanization as a major driver of urban climate change. *Adv Clim Chang Res* 6: 1–6. <https://doi.org/10.1016/j.accre.2015.08.003>
- Reyes R, Schueftan A, Ruiz C, et al. (2019) Controlling air pollution in a context of high energy poverty levels in southern Chile: Clean air but colder houses? *Energy Policy* 124: 301–311. <https://doi.org/10.1016/j.enpol.2018.10.022>
- Sadorsky P (2014) The effect of urbanization on CO<sub>2</sub> emissions in emerging economies. *Energy Econ* 41: 147–153. <https://doi.org/10.1016/j.eneco.2013.11.007>
- Schlosberg D (2012) Climate justice and capabilities: A framework for adaptation policy. *Ethics Int Aff* 26: 445–461. <https://doi.org/10.1017/S0892679412000615>
- Shahbaz M, Sarwar S, Chen W, et al. (2017) Dynamics of electricity consumption, oil price, and economic growth: Global perspective. *Energy Policy* 108: 256–270. <https://doi.org/10.1016/j.enpol.2017.06.006>
- Shi K, Xu T, Li Y, et al. (2020) Effects of urban forms on CO<sub>2</sub> emissions in China from a multi-perspective analysis. *J Environ Manag* 262: 110300. <https://doi.org/10.1016/j.jenvman.2020.110300>
- Simcock N, Walker G, Day R (2017) Fuel poverty in the UK: Beyond heating? *People Place Policy* 10: 25–41. <https://doi.org/10.3351/ppp.0010.0001.0003>

- Sy SA, Mokaddem L (2022) Energy poverty in developing countries: a review of the concept and its measurements. *Energy Res Soc Sci*. 89: 102562. <https://doi.org/10.1016/j.erss.2022.102562>
- Ulucak R, Khan SUD (2020) Determinants of the ecological footprint: Role of renewable energy, natural resources, and urbanization. *Sustain Cities Soc* 54: 101996. <https://doi.org/10.1016/j.scs.2019.101996>
- Voumik LC, Islam MA, Ray S, et al. (2023) CO<sub>2</sub> emissions from renewable and non-renewable electricity generation sources in the G7 countries: Static and dynamic panel assessment. *Energ* 16: 1044. <https://doi.org/10.3390/en16031044>
- Vurro G, Santamaria V, Chiarantoni C, et al. (2022) Climate change impact on energy poverty and energy efficiency in the public housing building stock of Bari, Italy. *Climate* 10: 55. <https://doi.org/10.3390/cli10040055>
- Wang Q, Zeng Y, Wu B (2016) Exploring the relationship between urbanization, energy consumption, and CO<sub>2</sub> emissions in different provinces of China. *Renew Sustain Energy Rev* 54: 1563–1579. <https://doi.org/10.1016/j.rser.2015.10.090>
- Wang WZ, Liu LC, Liao H, et al. (2021) Impacts of urbanization on carbon emissions: an empirical analysis from OECD countries. *Energ Policy* 151: 112171. <https://doi.org/10.1016/j.enpol.2021.112171>
- Westerlund J (2007) Testing for error correction in panel data. *Oxf Bull Econ Stat* 69: 709–748. <https://doi.org/10.1111/j.1468-0084.2007.00477.x>
- World Bank (2024) EE+EA: enhancing the World Bank's energy access investments through energy efficiency. Available from: <http://documents.worldbank.org/curated/en/2015/07/24819836/eeea-enhancing-world-bank?s-energy-access-investments-through-energy-efficiency>.
- Xu B, Lin B (2015) How industrialization and urbanization impact CO<sub>2</sub> emissions in China: evidence from nonparametric additive regression models. *Energy Econ* 48: 188–202. <https://doi.org/10.1016/j.eneco.2015.01.005>
- Zaman QU, Wang Z, Zaman S, et al. (2021) Investigating the nexus between education expenditure, female employers, renewable energy consumption and CO<sub>2</sub> emission: Evidence from China. *J Clean Prod* 312: 0959–6526, <https://doi.org/10.1016/j.jclepro.2021.127824>.
- Zhao J, Zhao Z, Zhang H (2021) The impact of growth, energy and financial development on environmental pollution in China: New evidence from a spatial econometric analysis. *Energy Econ* 93: 104506. <https://doi.org/10.1016/j.eneco.2019.104506>



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