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Energy Poverty and Environmental Quality Nexus: Empirical Evidence from Selected South Asian Countries

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Abstract

South Asian countries are included in the economies of developing Asia. The region of South Asia is predominantly affected by energy poverty issues due to a heavy reliance on conventional energy and unpredictable access to energy services. It has about a quarter of the world's population and is home to three of the world's ten most populated countries: India, Pakistan, and Bangladesh. This study investigates environmental sustainability dynamics in South Asian countries from 2000 to 2021, utilizing the Cross-sectional Autoregressive Distributed Lag (CS-ARDL) and Dumitrescu-Hurlin (D-H) causality methods. The research offers insights into the long-term trends and causal relationships that shape environmental outcomes in South Asian nations. Based on empirical findings, in the long-term, it is revealed that increases in energy poverty, economic growth, income inequality, and capital formation raise greenhouse gas (GHG) emissions, while renewable energy and labor reduce GHG emissions. On the other hand, the error correction term shows the speed of adjustment toward equilibrium at 0.75%. Furthermore, the D-H panel causality reveals a directional link between variables. These findings highlight the urgent need for South Asian countries to implement policies to address energy poverty, promote renewable energy adoption, and reduce income inequality to mitigate GHG emissions and achieve long-term environmental sustainability effectively.

1. Introduction

In energy economics literature and strategic documents, the growing problem of energy deprivation has given rise to the concept of energy poverty [1–3]. Nowadays, energy poverty is one of the key determinants that differentiates developing countries from developed ones [4, 5]. Accordingly, the level of access to and consumption of clean energy distinguishes energy-poor households from energy non-poor households [4, 6]. Every nation in the world is working to address energy issues [7]. Pursuing energy is always a main objective and a critical stage in advancing human life [8]. The absence of modern energy affects numerous aspects of human development at the household, community, and national levels [9, 10]. Energy poverty is a significant challenge in the energy sector because it is both a cause and consequence of poverty, which remains a reality for millions of people worldwide [11].

Energy poverty has been defined in various ways, including the inability to afford adequate advanced energy services (Boardman, [12]), the "Low Income High Cost" framework (Hills, [13]), the "Minimum Income Standard" (Moore, [14]), and concepts like "domestic energy deprivation" or "energy precariousness" (Bouzarovski, [15]). These definitions are often linked to 'fuel poverty' in developed countries [16–18]. The energy and fuel poverty concept first emerged in Europe during the oil crisis of the early 1970s in the United Kingdom (UK), highlighting the inability to purchase energy services. The term "energy poverty" was introduced in 1979 by Isherwood and Hancock [10, 17]. Two decades later, Boardman [19] used the term “fuel poverty” to describe a situation in which a household spends more than 10% of its income on fuel to maintain a suitable indoor temperature [17]. As a result, "fuel poverty" primarily describes situations in developed countries where households lack disposable income to meet basic energy needs, while "energy poverty" is often used in developing countries to refer to the lack of direct access to modern energy services [9, 10, 17, 20, 21].

In the Global South, particularly in South Asian countries such as Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka, energy poverty is defined by a lack of access to clean and modern fuels [16, 18, 22]. For instance, Reddy et al. [23] defined energy poverty as “the absence of sufficient choice in accessing adequate, affordable, reliable, quality, safe, and environmentally benign energy services to support economic and human development.” International Energy Agency (IEA) [24] described energy poverty as a lack of access to electricity, clean fuels, and energy infrastructure coupled with a heavy reliance on conventional fuels (e.g., biomass). These definitions are particularly relevant to developing countries, including those in Asia. Consequently, "energy poverty" is frequently used when investigating clean fuel accessibility in developing regions, such as South Asia [16].

Widespread energy poverty poses significant challenges to the global energy system. Approximately 770 million people worldwide live in energy poverty [25], with Africa, South Asia, and Central Asia being the most energy-poor regions [26]. Furthermore, 2.3 billion people globally still lack access to clean cooking, relying instead on outdated fuels like solid biomass, kerosene, or coal [27]. This issue is particularly severe in developing nations due to inadequate infrastructure and lack of access to modern energy [18]. Despite improvements in electricity access, around 1.2 billion people—or 55% of the population in developing Asia—still lack clean cooking facilities. This challenge will persist beyond 2030, with an estimated 760 million people expected to remain without access to clean cooking facilities in developing Asia by 2030 [27]. As such, achieving Sustainable Development Goal (SDG) 7, which aims to provide access to affordable, reliable, sustainable, and modern energy by 2030, will likely fall short.

While income poverty has long been a top priority in both short- and long-term economic development goals, addressing global energy poverty has also gained prominence [10]. The United Nations (UN) launched the "Sustainable Energy for All" initiative in 2001 to combat global energy poverty. By 2015, energy poverty was officially included in SDG 7 to ensure universal access to affordable, reliable, sustainable, and modern energy by 2030. SDG 7.1 outlines critical goals for affordable and clean energy, with two key indicators: (i) the proportion of the population with access to modern energy (electricity), and (ii) the proportion of the population reliant on clean fuels and advanced technology [28]. For a long time, the World Health Organization (WHO) has been concerned about indoor air pollution caused by solid fuel combustion [29], while the World Bank has promoted clean cooking practices and modern fuels. The goal underscores the importance of access to modern, clean fuels for improving human lives, reducing pollutant emissions, and ensuring sustainability and development [17, 18, 30–32]. As a result, addressing energy poverty has become a significant agenda for both research and practice in developed and developing countries [10, 33–36], especially in developing regions like South Asia [16].

In the twenty-first century, climate change, global warming, and environmental degradation have emerged as critical issues [37–41]. Human activity is increasingly blamed for the record levels of greenhouse gas (GHG) emissions in the atmosphere [42]. GHG emissions from fossil fuel combustion and deforestation have driven climate change and pose significant threats to human life, the environment, development, and sustainability [43]. Energy poverty in developing regions is characterized by heavy reliance on traditional fuels (biomass) and the lack of access to modern, clean cooking technology [44, 45]. This reliance has profound environmental impacts, contributing to GHG emissions and environmental degradation [46]. Deforestation caused by the unsustainable harvesting of biomass and the use of inefficient biomass-burning stoves for cooking and heating is a significant contributor to GHG emissions in Asian countries [10, 16, 34, 47]. Consequently, households' lack of access to clean cooking fuels indicates their dependence on low-efficiency traditional biomass, such as firewood and charcoal, leading to increased GHG emissions and environmental degradation [48–50]. The inefficient use of biomass in open-fire stoves produces smoke and releases methane along with other emissions [51]. Carbon dioxide (CO_2) emissions, which account for nearly 60% of GHG emissions, are not only a major contributor to climate change and environmental degradation but also pose serious risks to human life, development, and sustainability [50, 52, 53].

Empirical evidence suggests that energy poverty contributes to indoor air pollution and has environmental consequences, including GHG emissions [54, 55]. Difficulties in accessing clean fuels lead to a high dependency on traditional biomass, firewood, charcoal-based energy sources, and inefficient cooking devices, all of which have high pollution levels [11]. Unsustainable harvesting and consumption of biomass increase CO_2 emissions [56]. These high pollution attributes put significant pressure on the environment and contribute to adverse environmental effects [35, 57, 58]. Several studies have demonstrated that energy poverty increases CO_2 emissions and significantly contributes to environmental degradation [10, 11, 30, 59].

Several factors contribute to environmental degradation, particularly in developing countries, including GDP growth, renewable energy expansion, globalization, income inequality, capital formation, and labor force dynamics. GDP growth drives increased industrial activity and energy consumption, producing higher GHG emissions [40, 43, 52, 60]. While renewable energy aims to reduce emissions, its development can initially raise emissions due to infrastructure demands and transitional reliance on non-renewable sources [42, 52, 61, 62]. Globalization intensifies emissions through increased production, transportation, and resource utilization [63–66]. Income inequality exacerbates this issue, as wealthier populations consume more energy and resources, contributing disproportionately to emissions [67, 68]. Similarly, capital formation through investments in infrastructure and industry often leads to carbon-intensive activities [69, 70]. Lastly, labor force expansion fuels higher production and consumption, particularly in fossil fuel-dependent sectors, further driving emissions [7, 37, 40]. Given their substantial impact on emissions, this research treats these variables as control variables.

While increasing access to clean energy is crucial for improving environmental quality, much of the existing research focuses on its impacts on health, education, inequality, and income. However, despite projected improvements in electricity access across South Asia by 2030, access to clean cooking fuels remains a significant challenge. This study aims to fill a gap in the literature by examining the nexus between energy poverty and environmental quality in South Asia, a relatively underexplored area. Specifically, it investigates the impacts of income inequality, energy poverty, economic growth, and globalization on environmental pollution in the region. Unlike previous studies focused on micro-level household analyses, this research adopts a macroeconomic perspective, analyzing cross-country effects and providing robust evidence on how clean fuel-based energy poverty affects the environment. This approach helps policymakers develop more effective short- and long-term strategies for reducing CO_2 emissions. Methodologically, this study builds on prior research by employing the Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) model and Dumitrescu-Hurlin (D-H) causality test, allowing for the exploration of both short- and long-term dynamic impacts as well as the causal relationship between energy poverty and GHG emissions. The remainder of the study is structured as follows: the second section reviews the literature, the third outlines the methodology, the fourth presents results and discussion, and the final section concludes with recommendations.

2. Literature Review

2.1. General Overview

Environmental sustainability, equitable access to energy, and energy security—often called the energy trilemma—are increasingly recognized as critical issues in the twenty-first century, particularly in climate change [37, 42, 71]. Low household income, high energy costs, and energy-inefficient structures directly affect energy poverty, a key component of this trilemma. It negatively impacts human development and the environment [72]. Energy is crucial for addressing development challenges like poverty, education, health, and inequality. Although access to modern energy services has improved globally over recent decades, many populations still lack access to clean fuels and technologies for cooking, lighting, and heating [73].

Recent literature distinguishes between two types of energy poverty: "energy access poverty," prevalent in developing nations with limited access to modern and clean energy services, and "energy expenditure poverty" or "fuel poverty," which affects households in developed nations due to low incomes and high energy costs [20]. According to IEA [24], energy poverty is the absence of environmentally friendly, low-carbon energy sources and efficient appliances. This forces reliance on conventional biomass fuel, which is burned in inefficient cooking devices, contributing to environmental degradation and health risks. Irrational and inefficient energy consumption patterns further contribute to high CO_2 emissions, hindering global efforts to reduce carbon emissions. Thus, energy poverty, particularly the lack of access to clean cooking fuels, is closely linked to environmental impacts such as increased CO_2 emissions.

2.2. Nexus Between the Environment and Selected Variables

In recent years, increased focus on energy poverty has led many researchers to investigate its link with pollution and climate change, particularly in developing countries with the most adverse effects. Energy poverty and GHG emissions are closely interlinked: higher levels of energy poverty lead to higher GHG emissions while alleviating energy poverty can help reduce these emissions [59, 74, 75]. For instance, a study conducted in China found that a 1% increase in energy poverty results in a 0.170% increase in CO_2 emissions. Moreover, inadequate development of energy management systems and a lack of energy investment hinder efforts to alleviate energy poverty, contributing to increased CO_2 emissions [11].

Several other studies have reported significant environmental degradation due to energy poverty [76–78]. Many people, particularly in developing countries, continue to rely on traditional biomass and conventional energy sources, which contribute to pollution and environmental degradation [52, 79, 80]. Energy poverty is thus a significant driver of global warming [81]. A recent study conducted in BRICS countries further confirmed that energy poverty positively impacts CO_2 emissions [71].

Economic growth, particularly GDP growth, often leads to increased industrial activity and energy consumption, which in turn results in higher GHG emissions. As industries expand and economies develop, energy demands rise, frequently relying on fossil fuels, intensifying emissions [40, 43, 52, 60]. While renewable energy aims to reduce emissions, its initial development can paradoxically increase them. This is due to the infrastructure required to build renewable energy systems and the temporary reliance on non-renewable sources during the transition. However, over time, renewable energy contributes to a cleaner environment by replacing carbon-intensive sources [42, 52, 61, 62].

Globalization and income inequality both contribute to rising GHG emissions. Globalization intensifies emissions by driving increased production, transportation, and resource utilization. As countries become more interconnected, the demand for goods and services rises, leading to greater energy consumption and higher carbon footprints from international trade, logistics, and manufacturing [63–66]. At the same time, income inequality exacerbates the issue, particularly in developing countries. As income inequality rises, wealthier populations consume more energy and resources, contributing disproportionately to emissions, while poorer populations rely on less efficient and more polluting energy sources [34, 67, 68]. Numerous studies have shown a positive correlation between income inequality and CO_2 emissions, meaning that environmental degradation worsens as income inequality grows [34, 67, 82, 83]. However, in some cases, rising income inequality may lead to reduced emissions, potentially due to shifts in consumption patterns or policies targeting the wealthy [84, 85].

Capital formation, especially through investments in infrastructure and industry, often triggers carbon-intensive activities. Infrastructure projects, particularly in construction and transportation, frequently rely on fossil fuels, contributing significantly to GHG emissions during their development phases [69, 70]. Similarly, an expanding labor force typically drives higher production and consumption, particularly in sectors dependent on fossil fuels. As more people enter the workforce, demand for energy, transportation, and manufactured goods increases, pushing emissions higher, especially in carbon-heavy industries [7, 37, 40].

2.3. Literature Summary and Research Gap

Energy poverty is a major contributor to both social and environmental problems [30, 86, 87]. Over the past two decades, academics have examined various effects of energy poverty, such as micro-level impacts like depression, health, and education, which directly affect households, and macro-level impacts, including carbon emissions and electricity demand [16]. However, despite the fact that increasing access to clean energy is seen as a crucial step in enhancing environmental quality, research that has made theoretical and empirical progress in illuminating the impact of energy poverty has mainly concentrated on its socioeconomic implications. Thus, the socioeconomic effects of energy poverty—such as health, education, inequality, and income—have piqued the interest of academics [25, 33, 86, 88–90].

Nowadays, the environmental repercussions of energy poverty, particularly the effects of GHG emissions, have become a key concern for many scholars [37, 39, 58, 71, 76, 77, 80, 81, 91]. The literature suggests that because many people still favor using conventional energy sources, which contribute to pollution, energy poverty has a detrimental impact on environmental quality and

Table 1. Summary of variables and data sources.

Types of Variables	Variable and Symbol	Description	Unit	Data Source
Independent	Energy Poverty (EP)	Access to clean fuels and technologies is a proxy measure of energy poverty. A lack of access to these technologies can increase CO_2 emissions.	Population with access to clean fuels (%)	WDI [92]
Dependent	Greenhouse Gas Emissions (GHG)	GHG emissions, primarily measured as CO_2 emissions, are a proxy for environmental degradation. Rising GHG emissions contribute to global climate change and environmental hazards.	Total GHG emissions in CO_2 equivalent (tons)	OWID [93]
Control	Gross Domestic Product (GDP) Per Capita	GDP is a key indicator of a country's economic performance, potentially influencing energy use and environmental impact.	USD (constant 2015)	WDI [92]
	Income Inequality (INEQ)	Income inequality reflects the distribution of income within a population. Higher inequality could affect access to clean energy.	GINI index	WDI [92]
	Renewable Energy (RE)	The total energy use comes from renewable sources such as wind, solar, and hydropower. Higher renewable energy use is expected to reduce GHG emissions.	Electricity per capita (kilowatt-hour, kWh)	OWID [93]
	Globalization (GLB)	Globalization captures the economic, social, and political dimensions of global integration. It may affect both economic growth and environmental policies.	Index (scale 0-100)	KOF index [94]
	Capital Formation (GFCF)	Capital formation represents investment in infrastructure and other fixed assets, which can influence a country's energy use and emissions.	Local currency units (constant)	WDI [92]
	Labor Force (LF)	The total number of individuals who are either employed or unemployed and actively seeking work.	Total person	WDI [92]

contributes to global warming. Consequently, energy poverty is putting more environmental pressure on these areas. There is still much research to be done on how energy poverty specifically affects carbon emissions in these nations. Only a few studies from these emerging nations have investigated the link between energy poverty in terms of access to clean cooking fuels and the environment [10]. To the best of our knowledge, no specific studies have explored the linkage between the lack of access to clean fuel-based energy poverty and the environment in the South Asian context. This study aims to fill this gap by investigating the impact of energy poverty on environmental degradation. Thus, it contributes to the body of knowledge by addressing two critical global issues: energy poverty and environmental quality.

3. Materials and Methods

3.1. Energy Poverty Measurement

Measuring energy poverty is a complex issue that varies depending on time and place. In developing countries, major energy poverty issues are linked to a lack of access to modern energy services, with the focus often geared towards energy access, as this forms the basis of energy poverty [20]. In the context of South Asia, part of the Global South, energy poverty is commonly perceived as a problem of limited or no access to clean and modern fuels [16, 18, 22]. For this study, we use the term 'energy poverty' and measure it based on the percentage of the population with access to clean fuels and technologies for cooking. In energy-poor countries, a large proportion of the population has limited or no access to alternative modern cooking services, such as gas or Liquified Petroleum Gas (LPG), relying instead on biomass for cooking and heating. This measurement aligns with the approach of energy accessibility, reflecting supply-side considerations at the macro level. People in developing countries, especially those in rural areas, are affected by this indicator-based energy poverty [10, 16, 18, 22, 30, 86].

3.2. Variable Description and Data Sources

This research focuses on South Asian countries, specifically Bangladesh, India, Nepal, Pakistan, and Sri Lanka. Other countries in the region, such as Afghanistan, Bhutan, and the Maldives, were excluded due to insufficient data. The study covers the period from 2000 to 2021, and data were sourced from various reliable databases, including the World Development Indicators (WDI) [92], Our World in Data (OWID) [93], and the KOF Globalization Index [94]. Table 1 provides a detailed overview of the variables used in the study.

3.3. Empirical Model and Estimation Procedure

This study explores the linkage between energy poverty and greenhouse gas (GHG) emissions, which serve as a proxy for measuring environmental degradation. Equation 1 presents the empirical model in line with recent literature on the determinants and sources of GHG emissions.

$$GHG = f\ (EP, GDP, RE, GLB, INEQ, GFCF, LF) \tag{1}$$

Where GHG represents greenhouse gas emissions, EP stands for energy poverty, GDP is gross domestic product, RE refers to renewable energy, GLB is globalization, INEQ denotes income inequality, GFCF is capital formation, and LF represents the labor force. Furthermore, Equation 1 is transformed into its logarithmic form in Equation 2.

$$lnGHG = \alpha_0 + \alpha_1 lnGHG_{it-j} + \alpha_2 lnEP_{it} + \alpha_3 lnGDP_{it} + \alpha_4 lnRE_{it} + \alpha_5 lnGLB_{it} + \alpha_6 lnINEQ_{it} + \alpha_7 lnGFCF_{it} + \alpha_8 lnLF_{it} + \varepsilon_{it} \tag{2}$$

Where subscript i = (1, 2,...., N) indicates the cross-sectional units (countries), and t = (1,...., T) represents the number of time periods. α_0 is the intercept, and ε_{it} stands for the random disturbance term.

This research employs the Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) model to explore both short-term and long-term dynamic impacts between energy poverty and GHG emissions. This model is considered dynamic by Pesaran & Smith [95] and offers advantages over fixed effects, instrumental variables, and other dynamic models such as GMM estimators [96]. It is particularly appropriate because it provides consistent and efficient results by including a sufficient number of lags, even with small samples and short time periods [97], which is the case in our study. Thus, the model will follow the form of an ARDL (p, q, q,..., q) as presented in Equation 3.

$$lnGHG_{it} = \sum_{j=1}^{p} \alpha_{ij}\, lnGHG_{it-j} + \sum_{j=0}^{q} \delta_{ij}\, X_{i,t-j} + \mu_i + \varepsilon_{it} \tag{3}$$

Furthermore, by rearranging Equation 3, it transforms into Equation 4.

$$\Delta lnGHG_{it} = \emptyset_i\ (lnGHG_{i,t-1} - \beta_{i,}X_{i,t}) + \sum_{j=1}^{p-1} \alpha_{ij} + \Delta lnGHG_{i,t-j} + \sum_{j=1}^{q-1} \delta_{ij}\, \Delta X_{i,t-j} + \mu_i + \varepsilon_{it} \tag{4}$$

Where X represents the vector of explanatory variables; $\emptyset_i$ is the speed of adjustment coefficient $\emptyset_i < 0$; β_i measures the long-term effect of the contributing factors on carbon emissions; $(lnGHG_{i,t-1} - \beta_{i,}X_{i,t})$ is the Error Correction Term (ECT); α_{ij} and δ_{ij} are the short-term dynamic coefficients; p and q represent the optimal lag orders; and μ_i is the constant term. It should be noted that ε_{it} is the random disturbance term, which is homoscedastic—having constant variance, serial independence, and normal distribution. In Equation 4, the model is a specific class of Error Correction Model (ECM) that allows coefficients to vary among units. However, this estimation method is applicable only if the variables in question are integrated of order I(0) or I(1). This approach is appropriate for both small and large samples [98, 99]. For long-term and short-term estimations, this study utilizes the CS-ARDL estimator [100], which allows the long-term parameters to remain constant across individual groups of nations while accommodating short-term estimations, error variances, and intercept heterogeneity. This model is considered efficient and reliable if the long-term conditions are satisfied. Regardless of whether the series is I(1) or I(0), the CS-ARDL model has the advantage of providing both long-term and short-term estimates simultaneously [98].

3.4. Justification for Selecting the Region of South Asia

South Asian countries are part of the economies of developing Asia. The region of South Asia is predominantly affected by energy poverty issues due to heavy reliance on conventional energy (31.36%) and unpredictable access to energy services. It is home to about a quarter of the world's population (23.95%) and includes three of the ten most populated countries: India, Pakistan, and Bangladesh [58, 101–103]. Approximately 29% of people in this region still cook using traditional biomass, and 23% lack access to electricity [72]. According to the IEA [104], most countries in this region, excluding the Maldives (100%), lack access to clean cooking facilities. The situation is worst in Bangladesh, where 75% of the population cannot access modern clean cooking. Other populous countries like India and Pakistan have access rates of 68% and 50%, respectively. Bhutan has made significant progress (86.6%), but access to clean cooking facilities remains low in Nepal (35%), Afghanistan (34.4%), and Sri Lanka (35%).

Thus, this region's lack of access to clean cooking fuels and technology contributes to widespread energy poverty. While the majority of South Asian countries are expected to achieve full electricity access by 2030, access to clean cooking fuels will remain a significant challenge. This motivates us to explore the link between access to modern clean cooking fuel technologies, energy poverty, and the environment in these economies.

3.5. Study Flow and Procedure

Based on the workflow in Figure 1, the study follows five key steps. First, data analysis includes descriptive statistics to explore relationships. Next, stationarity tests (CADF and CIPS) ensure data stability in the model. The third step, cointegration tests (Johansen and Kao), checks for long-term relationships. Then, estimation uses CS-ARDL for both short- and long-term analysis, along with D-H panel causality tests to examine relationships between variables, followed by discussions.

Table 2. Descriptive statistics.

Variable	lnGHG	lnEP	lnGDP	lnRE	lnGLB	lnINEQ	lnGFCF	lnLF
Mean	19.1556	3.1768	6.9622	4.3997	3.9214	3.8700	28.8014	17.4796
Median	19.0617	3.2445	6.9507	4.9631	3.9609	3.8547	28.8767	17.7744
Max.	22.0845	4.2641	8.3867	5.8199	4.1376	4.0038	31.5185	20.0454
Min.	17.1816	1.7047	5.4103	1.1643	3.4711	3.7825	25.3595	15.6104
Std. Dev.	1.5799	0.5333	0.7091	1.2904	0.1605	0.0521	1.4045	1.5415
Obs.	110	110	110	110	110	110	110	110

Table 3. The results of cross-sectional dependency test.

Test	Stat.	Prob.
Breusch-Pagan LM	35.0186*	0.0001
Pesaran scaled LM	5.5943*	0.0000

Note: * indicates a 1% level of significance.

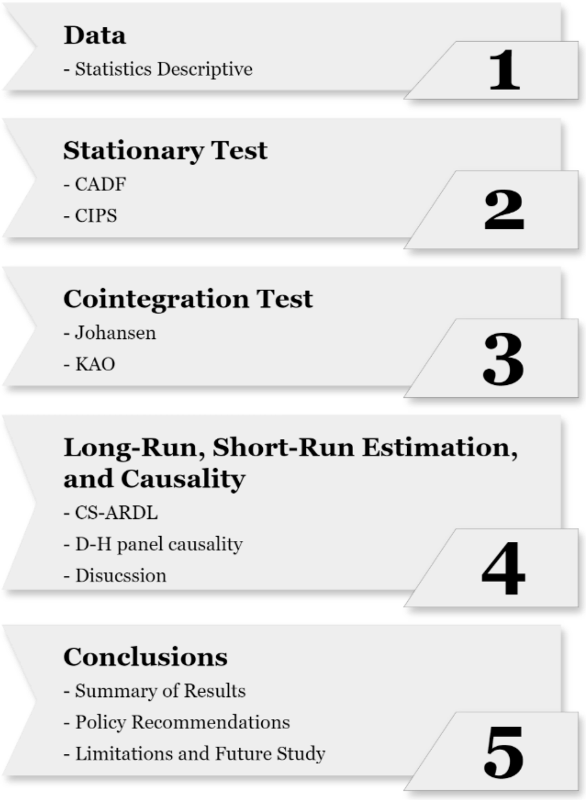

Figure 1. Workflow of the study

Finally, the conclusions summarize findings, offer policy recommendations, and outline limitations and future research directions.

4. Results and Discussion

4.1. Descriptive Statistics

Statistical Table 2 presents descriptive statistics for eight key variables based on panel data from South Asian countries, using logarithmic transformations to standardize differing measurement units. The dataset comprises 110 observations, with GHG emissions showing a mean of 19.16, suggesting some skewness in emission levels across the region. EP displays a mean of 3.18 and a relatively small standard deviation, indicating a more uniform distribution. In contrast, both GDP and GLB exhibit symmetry in their distributions, as evidenced by the close alignment between their mean and median values. However, RE and GFCF demonstrate significant variability, with higher standard deviations reflecting disparities in renewable energy use and capital formation. Furthermore, the higher mean value for the LF variable highlights considerable diversity in workforce size, while the larger standard deviations for GFCF and LF underscore heterogeneity in national investment levels and labor force composition across the region. These findings collectively reveal substantial variability in economic and energy indicators, reflecting the diverse socio-economic and energy landscapes of South Asia.

4.2. Cross-Sectional Dependency Tests

In this study, we utilized Cross-Sectional Dependence (CSD) tests [105], specifically the Breusch-Pagan LM and Pesaran scaled LM methods, to examine the interconnectedness of variables across South Asian countries. As shown in Table 3, the results from both tests are highly significant, with the Breusch-Pagan LM yielding a test statistic of 35.0186 (p-value = 0.0001) and the Pesaran scaled LM showing a test statistic of 5.5943 (p-value = 0.0000). These values decisively reject the null hypothesis of no cross-sectional dependence, strongly indicating the presence of CSD in the dataset. This finding suggests that changes in one country's GHG emissions or other related variables are likely to affect those of neighboring countries. The significant presence of CSD highlights the importance of considering regional interdependence in environmental and economic policies, as developments in one high-emitting country can potentially influence others within the region.

4.3. Unit Root Tests

Table 4 presents the outcomes of unit root tests conducted in South Asian countries. These tests encompass measurements concerning the presence of

Table 4. The results of CADF and CIPS unit root tests.

Variable	Level		1st Diff.		**Conclusion**
	t-stat.	**Prob.**	**t-stat.**	**Prob.**	
CADF					
lnGHG	1.8208	0.9657	-3.8358*	0.0001	I (1)
lnEP	2.4218	0.9923	-2.7589*	0.0029	I (1)
lnGDP	0.6712	0.7489	-3.8775*	0.0001	I (1)
lnRE	0.2087	0.5827	-5.8223 *	0.0000	I (1)
lnGLB	-2.8541*	0.0022	-2.1225**	0.0169	I (0)
lnINEQ	-2.2738**	0.0115	-1.9461**	0.0258	I (0)
lnGFCF	0.7111	0.7615	-4.2732*	0.0000	I (1)
lnLF	2.9735	0.9985	-4.0896*	0.0000	I (1)
CIPS					
lnGHG	-1.6501	> 0.10	-3.4085*	< 0.01	I (1)
lnEP	-2.6482*	< 0.01	-2.0018	> 0.10	I (0)
lnGDP	-2.8431*	< 0.01	-2.2543	< 0.10	I (0)
lnRE	-2.1653	> 0.10	-3.2375*	< 0.01	I (1)
lnGLB	-2.5593**	< 0.05	-1.9768	> 0.10	I (0)
lnINEQ	-2.7792*	< 0.01	-1.8781	> 0.10	I (0)
lnGFCF	-1.5399	> 0.10	-3.1790*	< 0.01	I (1)
lnLF	-2.7630*	< 0.01	-0.8600	> 0.10	I (0)

Note: ** and * indicate significance levels of 5% and 1%, respectively.

Table 5. The results of the cointegration tests.

Johansen Cointegration Test				
Null Hypothesis	**Fisher Stat.* (from trace test)**	**Prob.**	**Fisher Stat.* (from max-eigen test)**	**Prob.**
R = 0	0.000	1.0000	0.000	1.0000
R ≤ 1	0.000	1.0000	0.000	1.0000
R ≤ 2	187.3*	0.0000	102.1*	0.0000
R ≤ 3	267.6*	0.0000	208.6*	0.0000
R ≤ 4	245.7*	0.0000	217.6*	0.0000
R ≤ 5	106.9*	0.0000	74.90*	0.0000
R ≤ 6	48.78*	0.0000	40.10*	0.0000
Kao Cointegration Test				
ADF	-2.3722*	0.0088		

Note: * indicates a 1% level of significance.

unit roots, considering both trend and intercept for various variables. The Cross-sectional Augmented Dickey-Fuller (CADF) results indicate that all variables are stationary in the first difference. Additionally, the analysis using the Cross-sectional Im, Pesaran, and Shin (CIPS) reveals that EP, GDP, GLB, INEQ, and LF exhibit stationarity at I (0), indicating that these variables are stationary at the level. Conversely, GHG, RE, and GFCF demonstrate stationarity at I (1), signifying stability at the first difference. Due to the presence of CSD and mixed-order stationarity in the data, it is recommended to employ the CS-ARDL approach to estimate the outcomes.

4.4. Cointegration Tests

The Johansen and Kao cointegration tests, as presented in Table 5, offer distinct insights into the cointegration relationships within the time series data. The results of the Johansen test reveal the existence of multiple cointegrating vectors, rejecting the null hypothesis for up to six relationships with a p-value of 0.0000 (R ≤ 2, R ≤ 3, R ≤ 4, R ≤ 5, and R ≤ 6). However, two relationships accept the null hypothesis with a p-value of 1.0000 (R = 0 and R ≤ 1). The inference drawn from these findings is the presence of a long-term equilibrium relationship. Furthermore, the KAO test solidly supports the presence of a cointegrating relationship in the panel time series data, as evidenced by an ADF statistic of -2.3722 and a p-value of 0.0088, suggesting a rejection of the null hypothesis of no cointegration and implying a common long-term equilibrium among the series.

4.5. The Results of Short-term and Long-term CS-ARDL Estimation

The CS-ARDL model analysis in Table 6 reveals key long-term relationships, showing that EP, GDP, INEQ, and GFCF have statistically significant positive impacts on GHG emissions, while RE and LF exhibit negative impacts. Specifically, a 1% increase in EP is associated with a 0.2629% rise in GHG emissions. Similarly, GDP shows a positive correlation with GHG emissions, where a 1% rise

Table 6. CS-ARDL model estimation results.

Variable	Coeff.	Std. Er.	t-stat.	Prob.
Long-term Estimation				
lnEP	0.2629*	0.0587	4.4775	0.0000
lnGDP	0.0921**	0.0404	2.2806	0.0263
lnRE	-0.0280**	0.0113	-2.4756	0.0162
lnGLB	0.1287	0.1077	1.1954	0.2368
lnINEQ	1.2933*	0.2799	4.6207	0.0000
lnGFCF	0.1634***	0.0917	1.7817	0.0800
lnLF	-0.6578*	0.1534	-4.2877	0.0001
Short-term Estimation				
ECT(-1)	-0.7470*	0.2575	-2.9009	0.0052
ΔlnEP	0.8502	1.2630	0.6731	0.5035
ΔlnGDP	0.1464	0.2114	0.6926	0.4913
ΔlnRE	-0.0476	0.0453	-1.0493	0.2984
ΔlnGLB	-0.6643**	0.3279	-2.0257	0.0474
ΔlnINEQ	0.1374	1.4125	0.0973	0.9228
ΔlnGFCF	-0.0075	0.1226	-0.0609	0.9516
ΔlnLF	0.7060	0.5838	1.2093	0.2315
C	13.8500*	4.7365	2.9241	0.0049

Note: ***, **, and * indicates significance level at 10%, 5% and 1%, respectively.

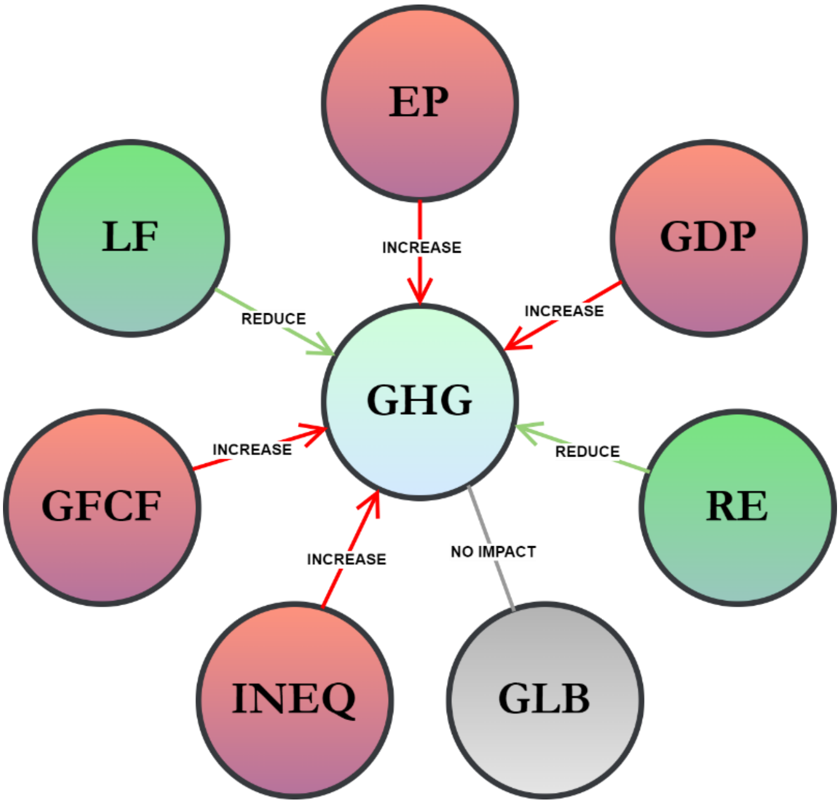

Figure 2. Graphical results of the long-term impact from the CS-ARDL estimation.

in GDP leads to a 0.0921% increase in emissions. INEQ also has a significant positive effect, with a 1% increase in INEQ leading to a 1.2933% rise in GHG emissions. GFCF follows this pattern, as a 1% increase results in a 0.1634% rise in GHG emissions. On the other hand, RE has a negative impact; a 1% increase in RE reduces GHG emissions by 0.0280%. Lastly, LF has a negative effect, where a 1% increase in LF reduces GHG emissions by 0.6578%. A visual representation of these long-term impacts is provided in Figure 2.

In the short term, the model's error correction term is -0.7470, indicating a robust mechanism by which approximately 74.70% of the deviation from the long-term GHG emission equilibrium is corrected each period. This finding underscores the existence of a strong adjustment process whereby emissions tend to revert to their equilibrium path relatively quickly after experiencing short-term shocks. The only other short-term variable with a statistically significant effect is GLB, which has a negative impact on GHG emissions,

Table 7. Short-term dynamics of cross-section units.

Variable	Bangladesh		India		Nepal		Pakistan		Sri Lanka	
	Coeff.	**Prob.**	**Coeff.**	**Prob.**	**Coeff.**	**Prob.**	**Coeff.**	**Prob.**	**Coeff.**	**Prob.**
ECT(-1)	-1.4898*	0.0000	-0.5102*	0.0001	-0.5109*	0.0001	-0.0525*	0.0000	-1.1714*	0.0007
ΔlnEP	-0.9652*	0.0085	0.3732	0.3734	0.2790**	0.0230	-1.1789	0.4903	5.7429	0.8243
ΔlnGDP	-0.1742*	0.0000	-0.0530*	0.0010	0.0116	0.1061	-0.0354*	0.0013	0.9831**	0.0213
ΔlnRE	0.0397*	0.0000	-0.0581*	0.0000	0.0660*	0.0007	-0.1083*	0.0000	-0.1771*	0.0003
ΔlnGLB	-0.1516**	0.0484	-1.3009*	0.0042	-0.5197*	0.0035	0.1803***	0.0575	-1.5295	0.3583
ΔlnINEQ	-2.0945**	0.0436	-3.2156	0.7721	0.4366	0.1988	0.5876*	0.0089	4.9731	0.7651
ΔlnGFCF	-0.4782*	0.0001	0.1800*	0.0001	0.0127*	0.0008	0.0577*	0.0006	0.1905	0.1097
ΔlnLF	0.1318	0.1813	0.2145***	0.0873	2.9389	0.1865	-0.4154**	0.0122	0.6601	0.8068

Note: ***, **, and * indicate the significance level at 10%, 5%, and 1%, respectively.

Table 8. The results of the D-H panel causality test.

Null Hypothesis:	**W-Stat.**	**Zbar-Stat.**	**Prob.**	**Direction between the Variables**
lnEP ≠ lnGHG	4.7046*	4.5655	0.0000	GHG ↔ EP
lnGHG ≠ lnEP	6.0040*	6.2229	0.0000	
lnGDP ≠ lnGHG	3.5675*	3.1152	0.0018	GHG ↔ GDP
lnGHG ≠ lnGDP	9.8039*	11.0693	0.0000	
lnRE ≠ lnGHG	1.9074	0.9979	0.3183	GHG → RE
lnGHG ≠ lnRE	3.0974**	2.5157	0.0119	
lnGLB ≠ lnGHG	4.2404*	3.9735	0.0001	GHG ← GLB
lnGHG ≠ lnGLB	1.1232	-0.0023	0.9982	
lnINEQ ≠ lnGHG	2.8891**	2.2500	0.0244	GHG ↔ INEQ
lnGHG ≠lnINEQ	3.8198*	3.4370	0.0006	
lnGFCF ≠lnGHG	4.9408*	4.8668	0.0000	GHG ↔ GFCF
lnGHG ≠ lnGFCF	5.8195*	5.9875	0.0000	
lnLF ≠ lnGHG	2.6270***	1.9157	0.0554	GHG ↔ LF
lnGHG ≠ lnLF	6.0522*	6.2843	0.0000	

Note: ***, **, and * indicates significance levels at 10%, 5%, and 1%, respectively. (→) and (←) denotes unidirectional causality, (↔) indicates bidirectional causality, and (≠) signifies that there is no causality.

suggesting that a 1% increase in GLB is associated with a decrease in GHG emissions by 0.6643%. The model underscores the intricate and varied influences of these factors on environmental outcomes, with both immediate and persistent effects on GHG emissions.

4.6. Short-Term Dynamics for Cross-Section Units

Table 7 presents the speed of adjustment towards long-term equilibrium after a shock measured by the ECT, which is found to be substantial across all countries, indicating that deviations from long-term GHG emission levels are corrected notably over time. Specifically, Bangladesh's GHG emissions adjust by approximately 1.4898% per period, India's by about 0.5102%, Nepal's by around 0.5109%, Pakistan's by 0.0525%, and Sri Lanka's by 1.1714%, all significant at the 1% level.

Short-term dynamics of cross-section units presented in Table 7 show distinct patterns emerging regarding the impact of various economic indicators on GHG emissions in South Asian countries. In Bangladesh, EP, GDP, GLB, INEQ, and GFCF exhibit a negative influence, with a 1% increase in each, resulting in a decrease in GHG emissions by 0.9652%, 0.1742%, 0.1516%, 2.0945%, and 0.4782%, respectively. Conversely, RE has a positive impact, contributing slightly to a 0.0397% increase in GHG emissions. In India, GDP, RE, and GLB have negative associations with GHG emissions, with a 1% increase in each contributing to decreases in GHG emissions by 0.0530%, 0.0581%, and 1.3009%, respectively. On the contrary, GFCF and LF have positive impacts, with a 1% increase in each leading to rises of 0.1800% and 0.2145% in GHG emissions, respectively. In Nepal, EP, RE, and GFCF positively affect GHG emissions, with a 1% increase in each contributing to increases in GHG emissions by 0.2790%, 0.0660%, and 0.0127%, respectively, while GLB is negatively associated; a 1% increase in it will lead to a 0.5197% decrease in GHG emissions. Furthermore, in Pakistan, GDP, RE, and LF have a negative impact on GHG emissions, resulting in reduced GHG emissions, with decreases of 0.0354%, 0.1083%, and 0.4154%, respectively. Conversely, GLB, INEQ, and GFCF are positively associated with GHG emissions, with a 1% increase in each contributing to increases in GHG emissions by 0.1803%, 0.5876%, and 0.0577%, respectively. Finally, in Sri Lanka, GDP has a positive impact, increasing GHG emissions by 0.9831%, while RE has a negative impact, contributing to a 0.1771% decrease. These findings highlight the diverse and nuanced relationships between economic indicators and GHG emissions across the region.

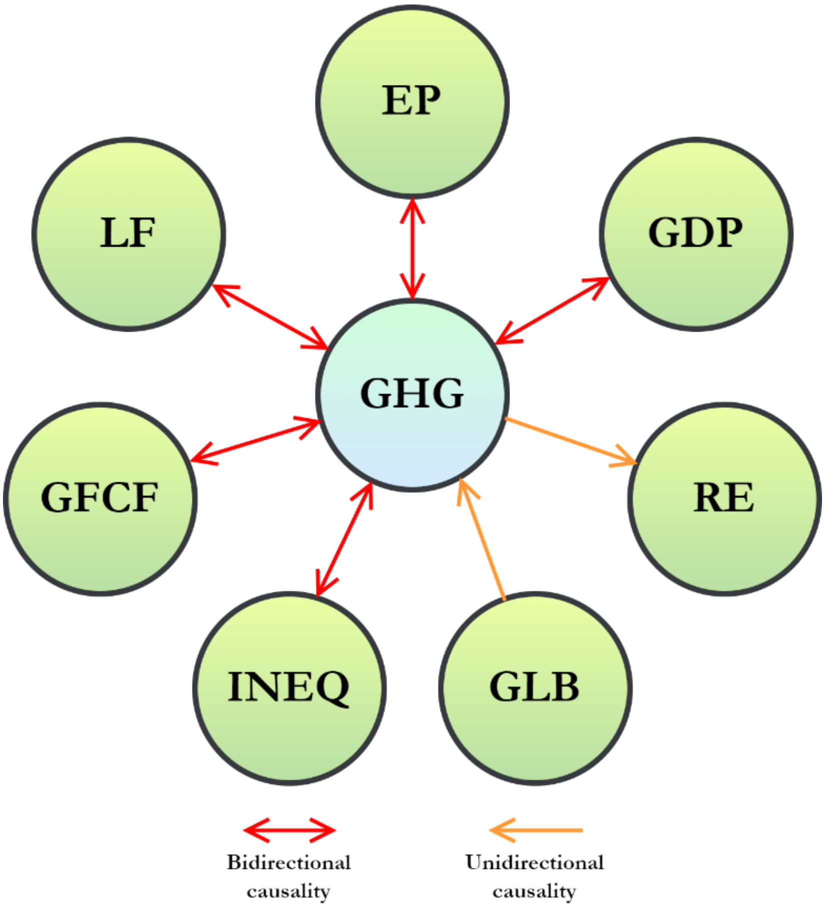

Figure 3. Overview of D-H panel causality results.

4.7. Dumitrescu-Hurlin Panel Causality

Based on the D-H panel causality results in Table 8, bidirectional causality exists between GHG emissions and EP, GDP, INEQ, GFCF, and LF, underscoring the intricate interdependence between environmental impact and key economic and social factors.

This bidirectional causality suggests a mutual influence, implying that changes in GHG emissions may be both influenced by and influencing fluctuations in energy poverty, economic growth, income inequality, capital formation, and the labor force. Furthermore, unidirectional causality was found from GHG emissions to RE and from GLB to GHG emissions. This implies that efforts to curb GHG emissions and promote renewable energy may positively influence adopting and developing renewable energy sources. Similarly, the unidirectional causality from GLB to GHG emissions suggests that globalization may impact environmental outcomes, emphasizing the importance of considering international economic dynamics in climate change mitigation strategies. Figure 3 presents an overview of the D-H panel causality analysis results.

4.8. Discussion

The findings of CS-ARDL models and the D-H panel causality test offer valuable understandings of the dynamics of these factors and their implications for environmental sustainability in South Asian countries. In the short-term, the results from the CS-ARDL reveal that only globalization has a significant, yet negative, effect on GHG emissions. This suggests that in the immediate period, increased globalization may lead to an emissions reduction in the region. This finding aligns with previous studies highlighting the potential for globalization to facilitate the adoption of cleaner technologies and more efficient production processes [106–108].

However, the long-term perspective paints a different picture. Energy poverty is identified as having a positive and significant long-term impact on GHG emissions. This result underscores the importance of addressing energy poverty not only as a social and economic challenge but also as a potential contributor to environmental degradation [11, 109]. The positive relationship implies that as energy poverty persists, reliance on environmentally harmful energy sources may increase over time [35].

Furthermore, economic growth has been found to have a positive and significant impact on GHG emissions in the long term. This result is consistent with the Environmental Kuznets Curve (EKC) theory, which posits that environmental degradation initially worsens with economic growth but eventually improves as societies reach a certain level of development [37, 39, 43, 110–113]. This suggests that South Asian countries may currently be in a phase where economic growth contributes to increased emissions, emphasizing the need for sustainable development practices.

Interestingly, renewable energy has been identified as having a negative and significant impact on GHG emissions in the long-term. This finding aligns with the expectations of environmentalists and policymakers who advocate for the transition to cleaner and sustainable energy sources. The negative coefficient suggests that an increase in the use of renewable energy is associated with a decrease in greenhouse gas emissions, emphasizing the potential of renewable energy as a mitigation strategy [39, 42, 52, 61, 62, 79, 114].

While globalization loses significance in the long term, income inequality has a positive impact on GHG emissions. As income inequality rises, wealthier groups consume more energy, while poorer populations rely on polluting energy sources, worsening environmental degradation [34, 67, 82, 83]. Furthermore, capital formation also positively impacts GHG emissions, meaning that investments in infrastructure and industrial expansion tend to increase energy consumption and GHG emissions [69, 70]. However, the labor force has a negative impact on GHG emissions, indicating that a larger workforce might contribute to more labor-intensive, less energy-intensive activities or greater awareness and adoption of sustainable practices, thereby reducing GHG emissions [37, 115].

The findings from the short-term dynamics of cross-sectional units reveal varied impacts of energy poverty, economic growth, renewable energy, globalization, income inequality, capital formation, and labor on GHG emissions across South Asian countries. In Bangladesh, addressing energy poverty could reduce environmental harm in the short term, aligning with clean energy theories. However, in Nepal, energy poverty increases GHG emissions, likely due to reliance on traditional energy sources, challenging the assumption that clean energy alone can mitigate environmental impacts. The lack of significant short-term effects in India, Pakistan, and Sri Lanka suggests that broader policies beyond energy poverty are needed. The impact of economic growth also varies: in Bangladesh, India, and Pakistan, economic growth appears to decouple from environmental harm, indicating that at a certain stage of growth, emissions may decline. Conversely, in Sri Lanka, economic growth increases emissions, suggesting the need for tailored policies. The effects of renewable energy are similarly mixed: it reduces emissions in India, Pakistan, and Sri Lanka, while in Bangladesh and Nepal it raises questions about the effectiveness of current strategies. Furthermore, globalization's impact is also mixed, with emissions decreasing in Bangladesh, India, and Nepal due to technology transfer and improved standards, while in Pakistan, globalization is linked to higher emissions, showing that its effects depend on the country's context. The effects of income inequality on GHG emissions are also mixed: it reduces emissions in Bangladesh but increases them in Pakistan. Similarly, capital formation reduces GHG emissions in Bangladesh while contributing to higher emissions in countries like India, Nepal, and Pakistan. Lastly, an increase in the labor force raises GHG emissions in India but reduces them in Pakistan.

The D-H panel causality test enhances the comprehensiveness and robustness of CS-ARDL findings. These findings highlight bidirectional causal links between GHG emissions and energy poverty, economic growth, income inequality, capital formation, and the labor force. This indicates a complex interplay in which factors such as energy poverty, economic growth, income inequality, capital formation, and the labor force affect emissions and are shaped by them. The presence of bidirectional causality underscores the need for holistic policies that address environmental concerns and socio-economic factors, aiming for a balanced and sustainable development approach.

Moreover, the unidirectional causality from GHG emissions to renewable energy suggests a reactive relationship. As emissions increase, there is a tendency for a shift towards cleaner energy sources. Formulating accurate strategies for this relationship that encourage renewable energy adoption in response to rising emissions can foster a positive feedback loop for sustainable development. On the other hand, the unidirectional causality from globalization to GHG emissions implies that economic integration into the global market may contribute to increased emissions. This calls for a careful balancing act, ensuring that economic growth through globalization is accompanied by environmental safeguards to mitigate the ecological impacts.

5. Conclusions and Policy Recommendations

This study investigates the impact of energy poverty on GHG emissions in South Asian countries from 2000 to

2021 using CS-ARDL and D-H causality tests. The empirical results highlight dynamics affecting environmental sustainability in the region. In the long term, energy poverty, income inequality, economic growth, and capital formation are identified as key drivers of increasing GHG emissions, underscoring the need to address socio-economic challenges alongside environmental issues. Conversely, renewable energy and labor are found to help mitigate environmental degradation by reducing GHG emissions. The study also emphasizes country-specific insights and highlights directional causality links between the variables, providing valuable insights for policymakers and researchers.

Based on this study's findings, several key policy measures are recommended for South Asian countries. First, alleviating energy poverty should be a priority to reduce its contribution to environmental degradation by expanding access to clean and affordable energy sources, such as solar and wind power, and implementing energy efficiency measures. Furthermore, country-specific renewable energy strategies must be developed and tailored to each nation's socio-economic and environmental contexts. This involves investing in research to identify the most suitable renewable energy sources and technologies, along with policies that promote their adoption and integration. Additionally, policies should adopt an integrated approach to sustainable development, addressing social and economic challenges alongside environmental concerns by promoting inclusive growth, reducing income inequality, and enhancing access to education, healthcare, and employment while ensuring environmental conservation and sustainable resource management. Recognizing the diversity of challenges across South Asian countries, policies must be tailored to each region's specific needs, with active involvement from local communities and stakeholders to ensure relevance and effectiveness. Furthermore, effective monitoring and evaluation of GHG emissions, energy use, and socio-economic indicators are vital for informed decision-making. These efforts will enable South Asian countries to advance sustainability, reduce energy poverty, and foster inclusive growth.

However, the study has limitations, including issues with data availability and various control variables that could enhance the results. Additionally, incorporating more modeling approaches could strengthen the robustness of the findings. Future research should focus on energy poverty-based EKC analyses, long-term impact assessments, sub-regional studies, evaluations of policy effectiveness, and comparative analyses with other developing regions. By addressing these limitations and pursuing these research directions, future studies can provide more comprehensive insights into achieving environmental sustainability in South Asia while promoting economic growth and social development.

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