Economic Growth and Environmental Sustainability: Empirical Investigation of Bangladesh, India, and Pakistan

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Cointegration, Economic growth, Carbon dioxide emissions, Renewable energy, South Asia.

Abstract
This paper examines the long- and short-term relationships between economic growth, trade, industrialization, renewable energy consumption, and environmental degradation in Bangladesh, India, and Pakistan from 1990 to 2022. It uses a panel autoregressive distributed lag (ARDL) approach and employs correlation analysis, panel cointegration tests, and pooled ARDL to capture the dynamic interactions among variables. The results indicate a positive long-term relationship between gross domestic product growth and carbon dioxide emissions, supporting the Environmental Kuznets Curve hypothesis. Trade and industrial growth also have a significant positive impact on emissions in the long run. Conversely, renewable energy consumption consistently shows a negative relationship with carbon dioxide emissions in both the short and long term, highlighting its importance in reducing environmental degradation. The agriculture sector displays a mixed impact, contributing to emissions primarily through land-use changes. The error correction term from the panel ARDL model is statistically significant, confirming long-run equilibrium relationships. The study finds robust evidence of cointegration among the variables, suggesting that the countries are on a convergent path in terms of balancing economic growth and environmental sustainability. Policy recommendations include the enforcement of stricter environmental regulations, promotion of renewable energy, and sustainable trade practices to mitigate environmental harm while fostering economic growth..

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1. Introduction

South Asian countries particularly Bangladesh, India, and Pakistan – has experienced remarkable economic transformation over the past three decades. Since the liberalization reforms of the early 1990s, these countries have integrated more deeply into the global economy through increased trade, foreign direct investment, and industrialization. The region has experienced significant economic expansion, with India becoming as one of the world's fastest-growing economies, while Bangladesh has shown impressive growth in sectors such as textiles and manufacturing (World Bank, 2021). Pakistan, although slower in growth compared to its neighbors, has made significant strides in industrial development and trade integration (Asian Development Bank, 2020). As these countries transitioned from primarily agrarian economies to industrial and service-based economies, environmental concerns have emerged due to increasing exploitation of natural resources and rising levels of pollution, particularly CO_2 emissions.

The environmental impact of rapid industrialization is well-documented in the literature, particularly in developing regions. The Environmental Kuznets Curve hypothesis predicts an inverted U-shaped link between environmental degradation and economic growth. This implies that environmental degradation increases during the initial stages of economic development but eventually declines as countries reach higher income levels and adopt cleaner technologies (Stern, 2004). However, empirical studies in South Asia, present mixed evidence on the validity of EKC hypothesis, suggesting that the benefits of economic growth do not automatically lead to environmental improvements without targeted policy interventions (Shahbaz *et al.*, 2016; Alam & Butt, 2021). The industrialization boom in South Asia has also raised concerns about the Pollution Haven Hypothesis (PHH), which posits that developing countries might attract polluting industries due to weaker environmental regulations (Cole, 2004). This has led to growing CO_2 emissions and resource depletion in the region, contributing to long-term environmental risks.

In recent years, South Asia has seen a tremendous push for renewable energy adoption, motivated by environmental concerns and the need for energy security. India, for example, has set aggressive renewable energy targets, intending to reach 450 gigawatts of capacity by 2030 (International Energy Agency, 2021). Bangladesh and Pakistan also attempt to enhance their renewable energy capacity, but these initiatives have fallen behind due to infrastructure restrictions and policy issues. Renewable energy is key in reducing CO_2 emissions and environmental degradation, as highlighted by global climate agreements such as the Paris Agreement (UNFCCC, 2015). However, the effectiveness of renewable energy adoption in significantly reducing environmental degradation in South Asia is understudied, particularly in light of rapid economic growth and industrialization.

Despite the expanding volume of literature on economic growth and environmental deterioration, few studies focus on South Asia, particularly after 2010. Most research focuses on larger emerging areas or individual nations, neglecting essential cross-country assessments that capture regional dynamics in South Asia. Moreover, the existing research frequently fails to incorporate recent economic trends, such as the surge in renewable energy investments and the region's evolving trade patterns. The current study aims to fill this gap by conducting a detailed examination of Bangladesh, India, and Pakistan from 1990 to 2022, focusing on how economic growth, trade, and renewable energy consumption impact environmental outcomes, particularly CO_2 emissions.

This study is topical and significant since it tackles South Asia's pressing need to strike a balance between economic growth and environmental sustainability. The region is currently at a crossroads, where its economic trajectory could either worsen environmental degradation or shift to a more sustainable development model. Given the growing global emphasis on reaching the Sustainable Development Goals, particularly Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action), understanding how economic policies affect the environment in fast-emerging countries such as South Asia is critical. This study will give policymakers evidence-based insights for developing methods that encourage long-term economic growth while minimizing environmental damage. Furthermore, by evaluating the role of renewable energy, the study contributes to a broader discussion on how green energy transitions might assist poor countries in meeting environmental commitments while maintaining economic development (World Bank, 2022).

While much study has been done on the relationship between economic expansion and environmental degradation, there remains a significant vacuum in understanding how these dynamics play out in South Asia, particularly in light of recent economic and regulatory changes. Much of the existing work on EKC and PHH is either obsolete or does not focus on the specific economic structures and environmental policies of Bangladesh, India, and Pakistan. Furthermore, few studies have thoroughly examined the role of renewable energy in mitigating environmental degradation in this region. Studies such as those by Alam & Butt (2021) and Shahbaz *et al.* (2016) have explored economic-environment linkages but lack updated analyses that incorporate the rapid increase in renewable energy adoption post-2010. Additionally, cross-country comparative studies focusing on South Asia are rare, leaving a gap in understanding how different policies and economic structures affect environmental outcomes across the region. This study addresses these gaps by offering an updated, comprehensive analysis that integrates economic growth, trade liberalization, industrialization, and renewable energy consumption within the framework of environmental sustainability. This study aims to compare both the short- and long-term impacts of economic growth, trade, renewable energy, population growth, industry, agriculture, and exports on environmental sustainability in Pakistan, India, and Bangladesh. This study will provide an in-depth understanding of the trade-offs between economic growth and environmental sustainability in South Asia. By filling the existing research gaps, it will contribute to the global discourse on sustainable development, offering actionable insights for policymakers aiming to achieve balanced and inclusive growth in the region.

2. Literature Review

This issue has been subject to considerable academic scrutiny in recent times, particularly relating to developing economies. South Asia represents a special case study in this respect: Bangladesh, India, and Pakistan have undergone rapid economic transformation through the effects of since the 1990s, and trade and FDI have been liberalized. However, all of this growth has raised several worries about environmental sustainability, including CO_2 emissions and overall environmental degradation. The critical assessment of empirical studies on the subject focused on the connection between economic policies and environmental repercussions for the South Asia region between 1990 and 2022. The analysis was structured around three main theoretical frameworks (EKC, PHH, and the Porter Hypothesis), allowing for a thorough and multidimensional assessment of complicated dynamics.

2.1. Theoretical Framework

2.1.1. Environmental Kuznets Curve (EKC) Hypothesis

The EKC hypothesis suggests an inverted U-shaped relationship between economic growth and environmental degradation. According to this theory, environmental degradation increases with the burgeoning industrial activities and rising energy use at the initial stages of economic development (Mohamed *et al.*, 2024). However, beyond a threshold point at higher incomes, further growth creates increased environmental awareness, better technology, and more stringent environmental regulation, which diminishes environmental degradation. This hypothesis was very relevant for Murshed and Dao's (2020) study of South Asia, particularly because countries like Bangladesh, India, and Pakistan started showing strong economic growth in the 1990s and have been registering rapid growth rates since then. If EKC is to be applied in such countries, then early industrialization and liberalization would have increased pollution, but environmental improvement could be achieved as these economies mature and support more intense environmental policy. The relevance of EKC to South Asia hinges upon debates on whether these countries have already attained or are getting close to an income level beyond which environmental deterioration would tend to decrease (Jóźwik *et al.*, 2022).

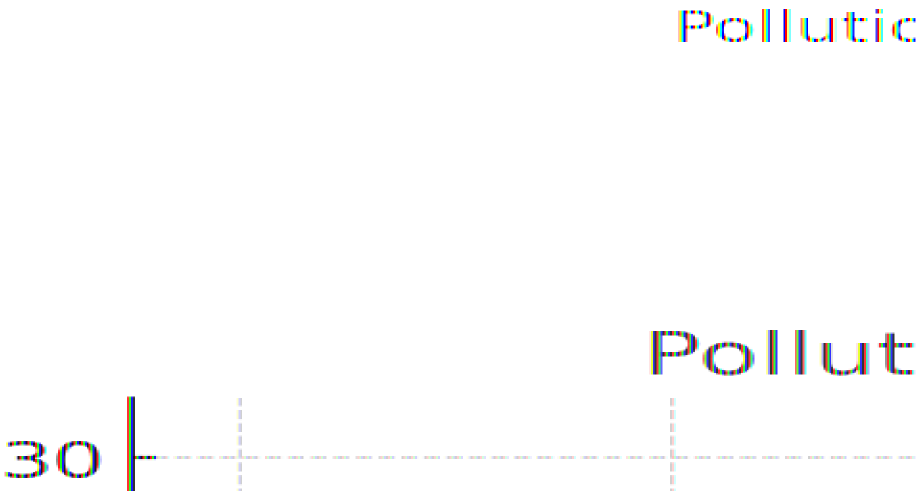

Figure 1. The Environmental Kuznets Curve
Source: Sadik-Zada and Loewenstein (2020)

2.1.2. Pollution Haven Hypothesis

PHH contends that trade liberalization and FDI can cause pollution-intensive industries to relocate from countries with strict environmental regulations to those with less stringent or poorly enforced environmental standards (Gill *et al.*, 2018). This theory suggests that developing countries, such as those in South Asia, might become 'pollution havens' as they attract FDI in sectors that are highly polluting due to their relatively lax environmental regulations. PHH is particularly pertinent to South Asia, where industrial growth has been fueled by trade liberalization and significant FDI inflow, particularly in industries like textiles, manufacturing, and mining, which are well-known for their negative environmental impact. The hypothesis raises critical concerns about the environmental consequences of economic policies that prioritize growth and investment over environmental protection and underscores the need for South Asian countries to strengthen their environmental regulations to avoid becoming dumping grounds for environmentally harmful industries.

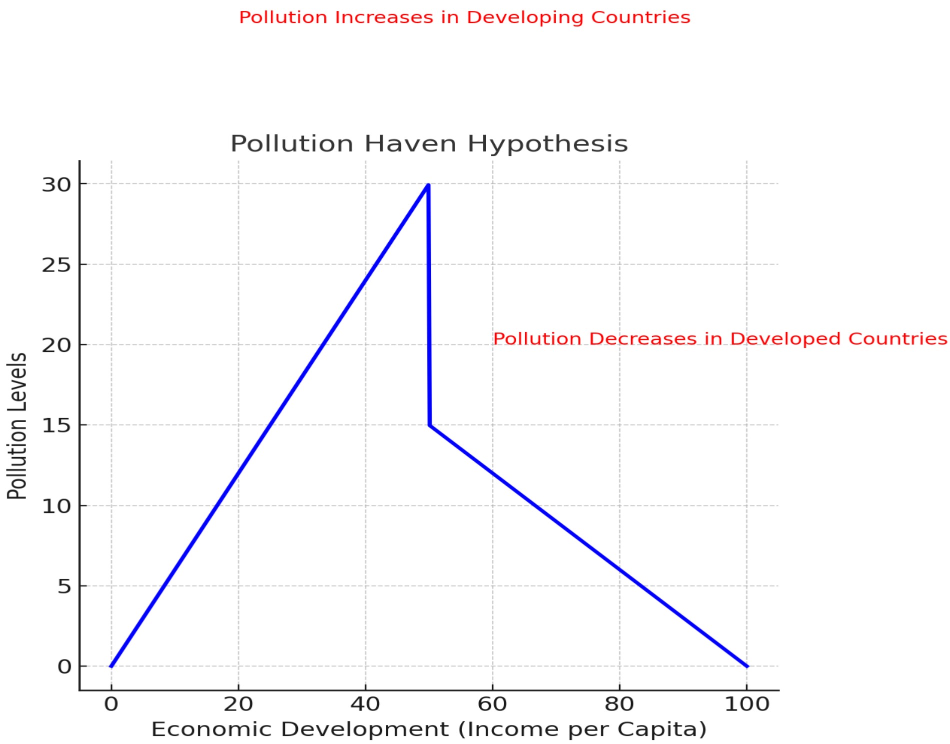

Figure 2. The Pollution Heaven Hypothesis
Source: Perman et al (2003)

2.1.3. Porter Hypothesis

The Porter Hypothesis proposes that strict environmental regulation is not detrimental to economic competitiveness. Rather, if appropriately designed, such regulation may drive innovation and competitiveness, thus resulting in enhanced environmental performance coupled with industrial growth (van Leeuwen and Mohnen, 2016). According to this hypothesis, the strictness of environmental requirements offers incentives for enterprises to innovate, therefore enhancing the efficiency of the production process by waste reduction and the development of environment-friendly products. The Porter Hypothesis is extremely optimistic about the ability of South Asian countries to convert environmental regulations into a driving force behind technological advancements and sustainable industrial growth (Twum *et al.*, 2021). Although South Asia's environmental regulations are comparatively weaker, according to the Porter Hypothesis, an eventual increase in stringency will drive the innovation which would significantly empower renewable energy, energy efficiency, and clean manufacturing, introducing qualitative improvements in both economic and ecological performance. The described theoretical framework presents the main approaches needed to explain how the dual objectives of industrial growth and environmental sustainability may be balanced in the case of the South Asian economies.

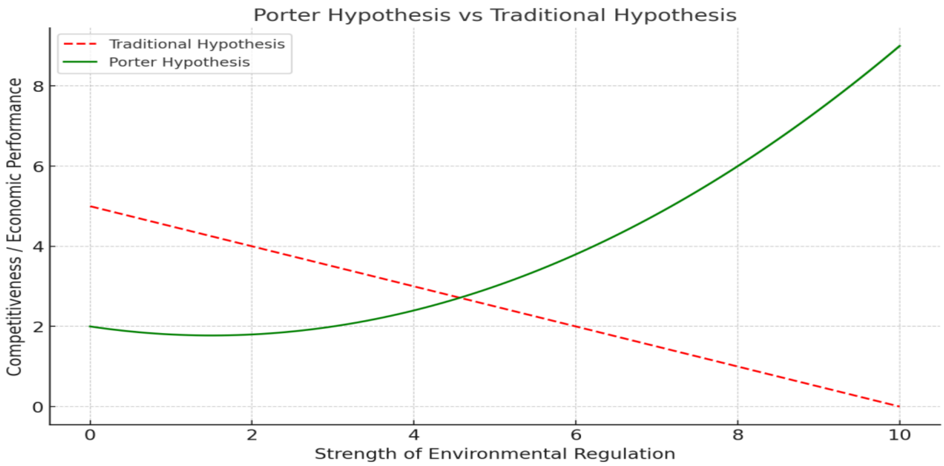

Figure 3. The Porter Hypothesis
Source Perman et al (2003)

2.2 Empirical Review

2.2.1. Trade Liberalization and Environmental Degradation

Maranzano, Bento and Manera's (2022) study is one of many that establish the groundwork for investigating the relationship between trade liberalization and environmental quality. Using panel data analysis across a wide range of countries, the study provided empirical support for the EKC theory. It concluded that while trade liberalization initially exacerbates environmental degradation due to increasing industrial activity, it eventually leads to improvements in environmental quality as income levels grow and societies demand cleaner settings. The inverted U-shaped relationship between economic expansion and environmental degradation is critical in understanding the potential long-term impacts of trade liberalization in South Asia. However, Maranzano, Bento and Manera (2022)'s study did not focus specifically on South Asian countries, and the period examined predates many of the significant trade liberalization policies implemented in the region in the 1990s and 2000s, presenting a research gap that newer studies can address.

Liu, Zhang and Liao (2021) further contributed to the discourse by analyzing how trade liberalization impacts pollution levels through the scale, technique, and composition effects. Their research employed a general equilibrium model alongside empirical data from various countries, revealing that trade liberalization's effect on pollution is multifaceted and context-dependent. They found that while the scale effect (increased economic activity leading to more pollution) could worsen environmental outcomes, the technique effect (adoption of cleaner technologies) and composition effect (shift towards less pollution-intensive industries) could mitigate or even reverse these impacts. This study is highly relevant for South Asia, where the composition of industrial growth following trade liberalization varies significantly across countries. However, Liu, Zhang and Liao (2021) did not provide a focused analysis on South Asia but China alone, particularly in the post-1990 period, leaving a gap for region-specific studies.

In contrast to previous research, Qamri *et al.* (2022) investigated the relationship between trade liberalization, FDI, and environmental deterioration in developing economies, including South Asian countries. Their analysis employed a dynamic panel data model to assess the long-term impacts of trade policies. The study found that while FDI inflows associated with trade liberalization initially led to higher pollution levels, over time, stricter environmental regulations and the transfer of cleaner technologies mitigated these effects, aligning with the Porter Hypothesis. This finding is particularly pertinent for South Asia, where FDI has played a crucial role in industrial development. Additionally, To *et al.* (2019) provided a more nuanced view than previous studies by incorporating the dynamic effects of regulatory changes and technology transfer. However, the study's generalization across all developing countries may overlook specific regional differences, such as the varying levels of industrial growth and environmental policy enforcement in countries such as Bangladesh, India, and Pakistan.

This study contributes to the literature by studying how renewable energy usage affects environmental pollution levels in South Asia. This research investigates the three hypotheses of EKC, PHH, and the Porter Hypothesis together as they operate in South Asia while showing how renewable energy implementation modifies these linkages. The study uses new data from 1990 to 2022 and, as such, provides contemporary policy recommendations and regional assessment findings. This research focuses on the economic-environmental trade-off by demonstrating how renewable energy systems help eliminate the negative influences of FDI and industrialization on carbon dioxide emissions. The research outcome demonstrates the necessity for specific policies that combine renewable energy promotion with sustained economic growth.

2.2.2. Industrial Growth and Environmental Degradation

The relationship between industrial growth and environmental degradation has been extensively researched, particularly in developing economies experiencing rapid industrialization. Hettige, Mani, and Wheeler (2000) undertook a detailed review of the factors influencing industrial pollution in emerging nations, including the role of industrial growth. Using a panel data set spanning 1973 to 1998, the authors discovered that industrial growth contributes significantly to environmental degradation, particularly in nations with lax environmental controls. This study supports PHH, implying that nations like Bangladesh, India, and Pakistan, which have witnessed significant industrial growth post-liberalization, are likely to face increased environmental deterioration unless severe environmental rules are enforced. However, the analysis is limited by its timeframe, which does not capture the more recent industrial developments and environmental policies in South Asia.

Saboori, Sulaiman, and Mohd (2012) investigated the effect of industrial expansion on CO_2 emissions in South Asian nations from 1980 to 2009. Using a panel cointegration technique, the study discovered that industrial growth had a major impact on regional CO_2 emissions. The authors contend that, while industrialization is necessary for economic progress, it also creates significant environmental concerns, particularly in the absence of adequate environmental controls. This study is especially noteworthy because it focuses on South Asia and covers a significant chunk of the period under consideration (1990-2022). However, like other studies, their study does not cover the most recent decade, missing out on the region's recent developments in industrial expansion and environmental policies.

Along a similar line, Shahbaz *et al.* (2014) investigated the link between industrialization, energy consumption, and CO_2 emissions in South Asia. The study used a vector error correction model to investigate long-term relationships and short-term dynamics. The data indicate that industrial growth, combined with high energy use, greatly raises CO_2 emissions in the region. The study emphasizes the need for South Asian countries to shift to more sustainable industrial practices and renewable energy sources to alleviate environmental damage. This study is directly relevant to the current study as it not only focuses on South Asia but also examines the role of industrial growth and energy consumption, two critical variables in the analysis of environmental degradation. However, as with other studies, its scope ends in 2011.

Raihan *et al.* (2022) conducted a more concentrated investigation of the relationship between industrial growth and environmental degradation in Bangladesh. Using time-series data from 1972 to 2007, the study discovered that industrial growth had a considerable impact on CO_2 emissions in Bangladesh. The authors contended that while industrialization is vital for economic development, it must be accompanied by appropriate environmental legislation to reduce its negative effects on the environment. This research is highly relevant to the current research as it focuses specifically on one of the South Asian countries under review and examines the impact of industrial growth on environmental degradation. However, the study's scope is limited to Bangladesh, and its timeframe ends in 2007.

2.2.3. FDI and Environmental Degradation

The relationship between FDI and environmental deterioration has been widely debated, particularly in developing nations. Demena and Afesorgbor (2019) conducted one of the first studies on this topic, examining the impact of foreign direct investment on environmental quality in emerging countries, including certain South Asian states. Using meta-analyses, the study discovered that FDI tends to flow into pollution-intensive businesses in nations with weak environmental restrictions, lending support to PHH. However, the study discovered that in some circumstances, FDI offers cleaner technologies and improved management practices, which can offset its negative environmental impact. This dual finding is particularly relevant for South Asia, where FDI has played a significant role in industrial development. However, the study's scope is limited by its focus on firm-level data, which may not capture the broader macroeconomic impacts of FDI on environmental degradation.

Hu *et al.* (2019) took a critical look at the relationship between FDI and environmental degradation, concluding that FDI in developing nations frequently contributes to environmental degradation, especially in the lack of rigorous environmental legislation. The study used cross-country regression analysis to investigate the impact of foreign direct investment on environmental quality in a sample of developing nations. According to the findings, countries with poor environmental standards are more likely to attract foreign direct investment in pollution-intensive industries, resulting in increased environmental degradation. This study is particularly pertinent to South Asia, where environmental rules have traditionally been less strict than in wealthier countries. However, like many other studies, Zarsky's analysis does not specifically focus on South Asia, and its timeframe does not cover the most recent decades.

In a more recent study, To *et al.* (2019) investigated the influence of FDI on environmental deterioration in developing nations, with a focus on the role of environmental legislation. Using panel data from 1990 to 2005, the authors discovered that FDI tended to exacerbate environmental deterioration in countries with inadequate environmental laws, while having a neutral or even positive influence in nations with strong environmental policies. The study's findings confirm PHH while also indicating that the negative environmental impact of FDI can be minimized with adequate environmental laws. This research is particularly relevant to South Asia, where FDI inflows have been substantial, but environmental regulations have varied across countries and over time. However, the study's timeframe ends in 2005, missing out on the more recent trends in FDI and environmental regulation in the region.

Similarly, Qamri *et al.* (2022) investigated the impact of FDI on environmental degradation in South Asian countries, using data from 1980 to 2012. The study employed a panel data analysis to examine the relationship between FDI, economic growth, and CO_2 emissions in the region. The findings suggested that while FDI contributes to economic growth, it also leads to higher CO_2 emissions, particularly in the short run. However, the study also found that the negative environmental impact of FDI diminishes over time as countries adopt cleaner technologies and improve their environmental regulations. This study is directly relevant to the current research as it focuses on South Asia and covers a substantial portion of the period under review (1990-2022). However, like many other studies, it stops short of the most recent decade.

2.2.4. Renewable Energy, Trade, and Environmental Degradation

The role of renewable energy in mitigating the environmental impact of trade liberalization and industrial growth is a growing area of research. Nguyen and Kakinaka (2019) analyzed the relationship between renewable energy consumption, economic growth, and CO_2 emissions in emerging economies, including some South Asian countries. Using panel data from 1994 to 2009, the study found that increased renewable energy consumption is associated with lower CO_2 emissions, supporting the argument that a transition to renewable energy can mitigate the negative environmental impact of industrial growth and trade liberalization. This finding is particularly relevant to South Asia, where the potential for renewable energy is substantial but remains underutilized. However, the study’s timeframe ends in 2009, missing out on more recent developments in renewable energy adoption.

In a similar vein, Khan, Rana and Ghardallou (2023) examined the causal relationship between renewable energy consumption, FDI, and CO_2 emissions in a sample of 54 countries, including some from South Asia. Using a panel data approach, the study found that while FDI contributes to higher CO_2 emissions, the negative impact can be offset by increased renewable energy consumption. The study's findings support the Porter Hypothesis, suggesting that FDI can lead to both economic growth and environmental improvements if it is accompanied by a shift towards renewable energy. This research is highly relevant to South Asia, where FDI has been a key driver of industrial growth, but its environmental impact has been mixed. However, the study's broad sample and focus on cross-country analysis limit its ability to provide specific insights into the South Asian context.

Saidi and Omri (2020) focused on South Asia and examined the influence of renewable energy consumption on CO_2 emissions in the region, utilizing data from 1990 to 2016. The authors used a panel cointegration approach to investigate the long-term relationship between renewable energy usage, economic growth, and CO_2 emissions. The findings revealed that greater renewable energy consumption is connected with lower CO_2 emissions in South Asia, showing the capacity of renewable energy to buffer the environmental impact of trade liberalization and industrial growth. This study is directly relevant to the current research as it focuses on South Asia and covers a substantial portion of the period under review (1990-2022). However, like other studies, it stops short of the most recent years.

2.2.5. Synthesis and Research Gaps

The empirical literature reviewed highlights the complex and multifaceted relationship between trade liberalization, industrial growth, FDI, and environmental degradation in South Asia. The studies reviewed provide evidence supporting the EKC hypothesis, with several studies suggesting that trade liberalization and industrial growth initially exacerbate environmental degradation but environmental quality will improve as income levels rise and civilizations demand cleaner settings. However, the data is contradictory, with some research indicating that trade liberalization and FDI can exacerbate environmental degradation, particularly in nations with more lax environmental standards.

The relevance of these studies to the current research lies in their focus on the key variables of interest—trade openness, industrial growth, FDI, CO_2 emissions, and renewable energy consumption—and their application of theoretical frameworks such as the EKC hypothesis, PHH, and the Porter Hypothesis. However, several research gaps remain. First, many of the studies \ do not cover the most recent decade (2010-2022), missing out on significant economic and environmental changes in South Asia. Second, while some studies focus specifically on South Asia, others provide more general analyses that may not fully capture the unique economic and environmental dynamics of the region. Finally, there is a need for more research that integrates the role of renewable energy in mitigating the environmental impact of trade liberalization and industrial growth, particularly in the context of South Asia.

3. Methodology

This study uses a quantitative research approach to investigate the relationship between economic growth and environmental sustainability in Bangladesh, India, and Pakistan between 1990 and 2022. To investigate these dynamics, the study utilizes a panel data analysis framework, which allows for the integration of cross-sectional (country-specific) and time-series (year-specific) data. Panel data offers a more robust analysis compared to purely cross-sectional or time-series data by accounting for both individual country-specific effects and variations over time (Baltagi, 2005). This technique enables the study to control for unobserved heterogeneity, improve the precision of parameter estimates, and provide insights into the long-run and short-run relationships between the variables.

Research data affirm the EKC hypothesis because it demonstrates how economic expansion at first damages the environment until development reaches higher stages. Research results challenge PHH to some extent because FDI's environmental effects depend on national environmental regulations and renewable energy usage rates. The results strengthen the identification of the Porter Hypothesis because tight environmental regulations drive industrial innovation which produces sustainable business practices. Explicit connections of theoretical perspectives to real data strengthen the theoretical cohesion in this work.

Table 1. Data Description

Variables	Indicators
Environmental degradation	CO_2 emissions (metric tons per capita)
International trade	Trade (% of GDP)
Economic growth	GDP growth (annual %)
Industry	Industry (including construction), value added (% of GDP)
Renewable energy	Renewable energy consumption (% of total energy consumption)
Agriculture and forestry production	Agriculture, forestry, and fishing, value added (% of GDP)
Population growth	Population growth (annual %)
Exports	Exports of goods and services (% of GDP)

Note: Data presented based on authors' own estimations by using WDI data

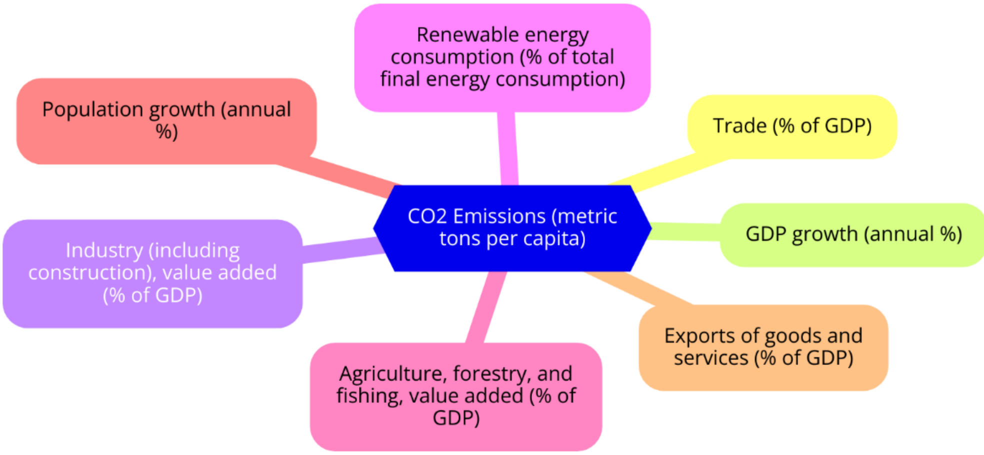

Figure 4. Variable structure
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The foundation of the approach is panel autoregressive distributed lag (ARDL) modeling, which is combined with cointegration tests to investigate the long-term equilibrium relationships between the variables. The ARDL approach is particularly appropriate for this study because it can handle variables of different orders (I (0) and I (1)) and does not require unit root pre-testing as other econometric techniques such as vector error correction models do (Pesaran *et al.*, 2001). Given the heterogeneous integration qualities of the variables—where some variables may be stationary at level and others after first differencing—the ARDL bounds testing method is excellent for validating the validity of the long-run relationships. This research adopts a positivist approach, relying on empirical evidence and statistical methods to draw objective conclusions about the relationships between variables. By using panel ARDL and cointegration techniques, the study can provide robust, generalizable findings that contribute to the broader literature on sustainable development in developing economies (Greene, 2012).

3.1. Model Specification

The model for this study is based on the panel ARDL framework, which examines both short-run and long-run relationships between the dependent variable (CO_2 emissions, representing environmental degradation) and a set of independent variables. The general form of the ARDL model is expressed as follows:

$$\Delta CO_{2it}=\alpha_0+j=1\sum p\beta_j \Delta X_{it-j}+\lambda(CO2_{it-1}-\gamma' X_{it-1})+\epsilon_{it}$$

The error correction term (ECT) captures the long-run equilibrium connection by indicating how rapidly deviations from it are repaired. A statistically significant and negative ECT coefficient implies that the system adjusts to restore equilibrium, implying long-term cointegration of the variables (Pesaran *et al.*, 2001). The ECT captures the long-run equilibrium connection by indicating how rapidly deviations from it are repaired. A statistically significant and negative ECT coefficient implies that the system adjusts to restore equilibrium, implying long-term cointegration of the variables (Pesaran *et al.*, 2001). In addition to the ARDL model, Johansen cointegration tests are used to confirm the existence of long-run relationships among the variables. The Johansen technique tests for the number of cointegrating vectors and helps identify the presence of stable long-term relationships between economic growth, trade, and environmental degradation (Johansen, 1991).

The panel ARDL model was used for this investigation because it has various advantages over other econometric models. First, it can handle variables with distinct integration orders (I (0) and I (1)), which is typical in macroeconomic data (Pesaran *et al.*, 1999). Second, the ARDL technique is adaptable in distinguishing between short-run and long-run dynamics, which is critical for understanding the immediate and long-term impacts of commerce, industrialization, and renewable energy on environmental outcomes. Unlike traditional models that assume all variables are either stationary or non-stationary, the ARDL model avoids pre-unit root testing and reduces the risk of incorrect specification (Shin *et al.*, 2014). Additionally, the panel data structure enhances the robustness of the results by controlling for country-specific heterogeneity, thus accounting for structural differences between Bangladesh, India, and Pakistan. This allows the study to draw more generalizable conclusions about the region while also identifying country-specific dynamics that may affect the environment differently in each case (Baltagi, 2005). By combining the ARDL and cointegration approaches, this study ensures a comprehensive analysis of the short-run and long-run relationships between economic and environmental factors, contributing to a deeper understanding of sustainable development challenges in South Asia.

4. Analysis and Results

4.1. Descriptive Statistics

The descriptive statistics for Pakistan, Bangladesh, and India from 1990 to 2022 reveal important trends in economic growth and environmental factors Table 2. Average CO_2 emissions were 0.703 metric tons per capita, reflecting industrial growth and some fluctuations. The agricultural sector remained significant, contributing 20.967% of GDP, while exports accounted for 14.164%, indicating sensitivity to global markets. GDP growth averaged 5.145%, with considerable volatility, ranging from -5.778% to 8.846%. The industrial sector contributed 24.403% to GDP, and population growth averaged 1.798%, impacting resource demands. International trade represented 32.804% of GDP, and renewable energy consumption averaged 46.976%, highlighting ongoing sustainability efforts. Overall, these findings underscore the need for integrated policies to promote economic growth and environmental sustainability in the region.

Table 2. Descriptive Statistics

Statistic	CO_2	AGRI	EXPO1	GDP	INDUSTRY	POP	TRADE	R_ENERGY
Mean	0.703	20.967	14.164	5.145	24.403	1.798	32.804	46.976
Median	0.683	21.787	12.675	5.240	23.581	1.788	31.334	47.200
Maximum	1.796	31.677	25.431	8.846	32.912	3.297	55.794	73.100
Minimum	0.099	11.975	5.908	-5.778	17.159	0.880	15.506	26.100
Std. Dev.	0.425	4.278	4.561	2.249	4.029	0.586	9.384	10.273
Observations	93	93	93	93	93	93	93	93

Results estimated using EViews 12 (authors' analysis).

4.2. Correlation Matrix

The correlation matrix Table 3 provides useful information on the relationships between various economic and environmental variables. There is a significant positive correlation (0.96) between exports and trade, implying that gains in exports contribute significantly to overall trade performance in these countries. Furthermore, there is a moderate positive connection (0.46) between CO_2 emissions and commerce, implying that increasing trade activity may be related with higher emissions, most likely due to increased industrial production and transportation operations. In contrast, the connection between CO_2 emissions and renewable energy consumption is highly negative (-0.63), implying that more reliance on renewable energy is associated with lower CO_2 emissions. This highlights the potential for renewable energy to mitigate environmental degradation in the region. The agricultural sector shows a negative correlation with both CO_2 emissions (-0.37) and trade (-0.69), indicating that as agricultural value-added increases, emissions may decrease, which could be attributed to less industrial activity or a shift towards more sustainable farming practices. The industrial sector also presents a mixed picture; while it correlates positively with CO_2 emissions (0.34) and trade (0.40), it shows a negative relationship with agricultural value added (-0.55), suggesting a trade-off between industrial growth and agricultural productivity. Furthermore, population growth displays a negative correlation with CO_2 emissions (-0.26), hinting that increasing population may not directly contribute to emissions growth, possibly due to the adoption of more sustainable practices. Overall, the correlation matrix underscores the complex interdependencies between economic activities and environmental impacts in India, Bangladesh, and Pakistan. These relationships emphasize the need for targeted policies that promote sustainable development while balancing industrial growth and environmental preservation.

Table 3. Correlation Matrix

Variable	CO_2	AGRI	EXPO1	GDP	INDUSTRY	POP	R_ENERGY	TRADE
CO_2	1							
AGRI	-0.37	1						
EXPO	0.55	-0.65	1					
GDP	0.07	-0.31	0.24	1				
INDUSTRY	0.34	-0.55	0.49	0.40	1			
POP	-0.26	0.63	-0.30	-0.26	-0.48	1		
R_ENERGY	-0.63	0.86	-0.56	-0.21	-0.54	0.59	1	
TRADE	0.46	-0.69	0.96	0.21	0.40	-0.37	-0.56	1

Results estimated using EViews 12 (authors' analysis).

4.3. Data Visualization

The data visualizations Graphs 1, 2 and 3 for Bangladesh, India, and Pakistan reveal key insights into the interplay between economic activities and environmental sustainability. CO_2 emissions have steadily increased across all three countries, driven by industrial growth and trade expansion. India, in particular, shows a significant rise in emissions due to its rapid industrialization and energy consumption, while Bangladesh's growth is more moderated. The trade sector plays a critical role in this, as export-driven industries, particularly energy-intensive ones like manufacturing, contribute to higher emissions levels. However, the graphs also underscore the importance of renewable energy, with a strong negative correlation between renewable energy consumption and emissions. India has made the most progress in this area, where greater reliance on renewables is visibly helping curb emissions growth. Agriculture, especially in Pakistan, exhibits a unique trend, where increased agricultural output seems to correspond with lower emissions, possibly due to the lower energy intensity of agricultural activities compared to industrial processes. Overall, the visual data highlight the potential of renewable energy and sustainable trade policies to mitigate the environmental impacts of economic growth in the three countries.

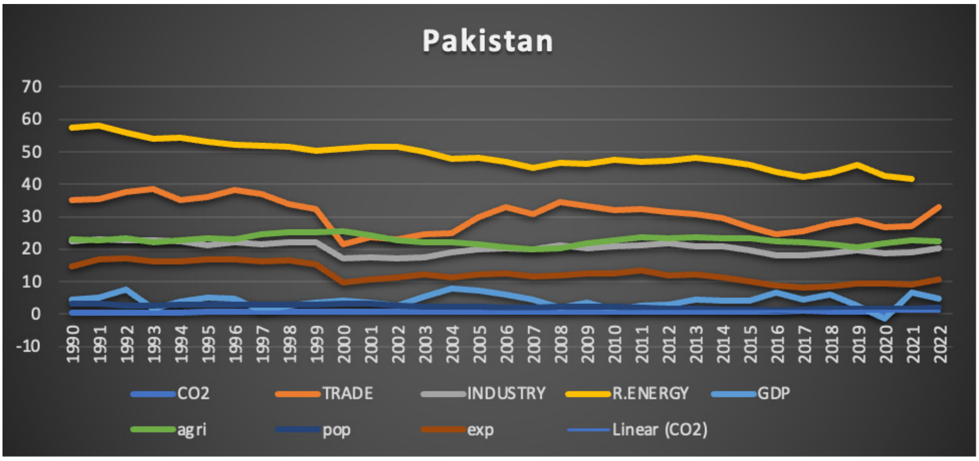

Figure 5. Data visualizations for Bangladesh
Results estimated using Microsoft Excel (authors' analysis).

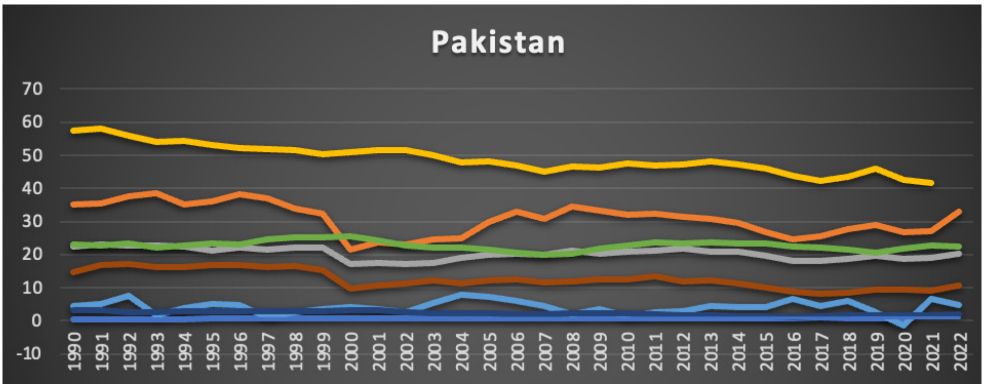

Figure 6. Data visualizations for India
Results estimated using Microsoft Excel (authors' analysis).

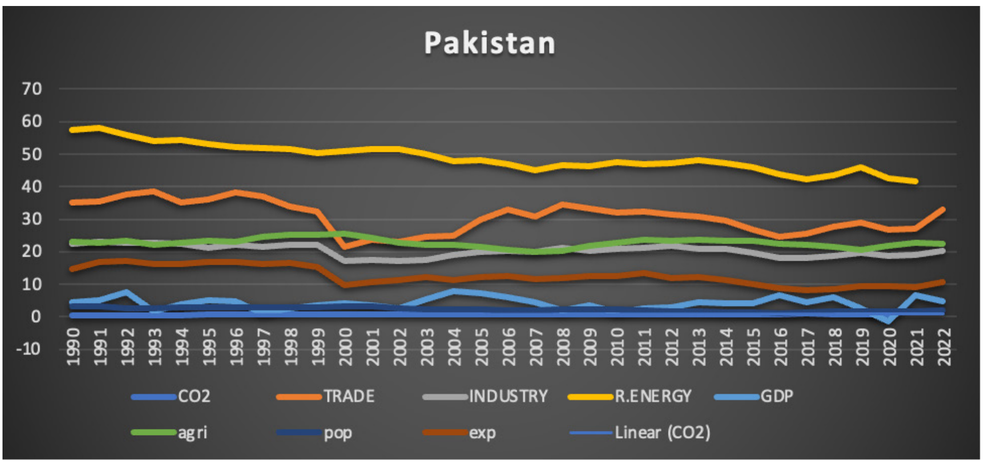

Figure 7. Data visualizations for Pakistan

Sources: Authors' calculation

4.4. Unit Root Test

The unit root test Table 4 results show that most variables, including CO_2 emissions, exports, GDP, industry, and trade, are non-stationary at the level but become stationary after initial differencing, resulting in I (1). Agriculture and renewable energy, on the other hand, remain stagnant at the level (I(0)). Given this set of integration orders, the panel ARDL model is appropriate, as it is especially beneficial for variables with varied integration orders (Pesaran *et al.*, 2001). It supports both short- and long-run research, and the limits testing method can detect potential long-term links (cointegration) between economic growth, trade, and environmental factors. This makes it a robust method for investigating dynamic relationships in cross-country panels, as emphasized in studies on time series with non-stationary variables (Narayan, 2005).

Table 4. Unit root test

Variable	ADF Statistic (Level)	Prob. (Level)	ADF Statistic (1st Diff)	Prob. (1st Diff)
CO_2	1.36718	0.9678	19.4525	0.003
AGRI	34.7011	0.0000		
EXP01	4.07563	0.6664	41.9148	0.0000
GDP	5.34384	0.5005	93.2123	0.0000
INDUSTRY	2.71507	0.8437	36.2577	0.0000
POP	8.77761	0.1865	37.3611	0.0000
R_ENERGY	33.5746	0.0000	25.4207	0.0003
TRADE	2.16448	0.9040	40.8371	0.0000

Sources: Authors' calculation

4.5. Cointegration Test

Table 5. Johansen Fisher Panel Cointegration Test Results

Hypothesized No. of CE(s)	Fisher Stat. (from Trace Test)	Prob.	Fisher Stat. (from Max-Eigen Test)	Prob.
None	239.4	0.000	100.8	0.000
At most 1	117.5	0.000	50.88	0.000
At most 2	76.41	0.000	27.29	0.000
At most 3	52.42	0.000	23.23	0.000
At most 4	33.60	0.000	18.29	0.005
At most 5	19.62	0.003	10.10	0.120
At most 6	14.72	0.022	8.979	0.174
At most 7	16.59	0.010	16.59	0.010

Sources: Authors' calculation

4.5.1. Individual Cross-Section Results for Cointegration Tests

The Johansen Fisher panel cointegration test results indicate strong evidence of long-term relationships among the variables across Pakistan, Bangladesh, and India. Both the trace and maxeigenvalue tests show significant cointegration at the "None" hypothesis, with Fisher statistics of 239.4 and 100.8 respectively, and probabilities of 0.0000, confirming at least one cointegrating relationship within the panel. This suggests the presence of multiple stable long-run relationships among variables such as CO_2 emissions, trade, GDP, industry, agriculture, and renewable energy. The country-specific results reinforce this, as each country exhibits significant cointegration at the "no cointegration" level, with Bangladesh, India, and Pakistan showing trace test statistics well above the critical values, all with probabilities of 0.0000. While the evidence of cointegration becomes weaker at higher ranks, there remains some level of long-run relationships up to "at most 4." These findings imply that despite short-term fluctuations, the variables maintain a stable longterm equilibrium, supporting the use of panel ARDL models to capture both short-run dynamics and long-run adjustments across these South Asian economies. This emphasizes the interconnectedness of economic growth, environmental factors, and trade in the region.

Table 6. Individual Cross-Section Results for Cointegration Tests

Hypothesis	Country	Trace Statistic	Prob.	Max-Eigen Statistic	Prob.
No Cointegration	Bangladesh (BGD)	302.2136	0.000	81.2687	0.000
	India (IND)	312.5051	0.000	109.6672	0.000
	Pakistan (PAK)	306.7814	0.000	116.3083	0.000
At most 1	Bangladesh (BGD)	220.9448	0.000	62.8161	0.000
	India (IND)	202.8379	0.000	69.1334	0.000
	Pakistan (PAK)	190.4731	0.000	62.5010	0.000
At most 2	Bangladesh (BGD)	158.1287	0.000	46.4061	0.008
	India (IND)	133.7045	0.000	48.2124	0.004
	Pakistan (PAK)	127.9721	0.000	42.2164	0.028
At most 3	Bangladesh (BGD)	111.7226	0.000	39.7396	0.008
	India (IND)	85.4921	0.001	39.4819	0.009
	Pakistan (PAK)	85.7558	0.001	31.0577	0.105
At most 4	Bangladesh (BGD)	71.9830	0.000	31.2061	0.016
	India (IND)	46.0102	0.074	24.5950	0.115
	Pakistan (PAK)	54.6981	0.010	27.1524	0.057
At most 5	Bangladesh (BGD)	40.7769	0.002	20.1739	0.068
	India (IND)	21.4153	0.332	13.6170	0.397
	Pakistan (PAK)	27.5457	0.089	15.7713	0.239

Sources: Authors' calculation

4.6. VAR Lag Order Selection Criteria

The VAR lag order selection criteria Table 7 indicate that the optimal lag length for the model is 1, based on multiple statistical measures. Specifically, the Akaike Information Criterion (AIC), Schwarz Criterion (SC), and Hannan-Quinn Criterion (HQ) all suggest the lowest values at lag 1, with the corresponding log likelihood (LogL) of -486.1907. Additionally, the Likelihood Ratio (LR) test and Final Prediction Error (FPE) also confirm lag 1 as the optimal choice, as the smallest FPE (0.000135) is found at this lag. The results imply that the VAR model with one lag is best suited for capturing the dynamic relationships among the variables, balancing model complexity and fit (Lütkepohl, 2005). This lag selection is crucial for ensuring an accurate representation of the short-term dynamics in the panel data analysis.

Table 7. Lag Length Selection Criteria

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-1274.588	NA	7830.831	31.66883	31.90532	31.76371
1	-486.1907	1401.595	0.000135*	13.78249*	15.91089*	14.63643*
2	-430.4489	88.08586*	0.000172	13.98639	18.00670	15.59939
3	-370.9226	82.30798	0.000216	14.09685	20.00907	16.46891
4	-313.3479	68.23663	0.000320	14.25550	22.05963	17.38662

Sources: Authors' calculation.

4.7. Panel ARDL

4.7.1. Short-run coefficients for each variable

The short-run coefficients from the panel ARDL model provide information on the factors' immediate and short-term effects on the dependent variable Table 8. The panel ARDL model results show a log-likelihood of 248.5902, indicating a strong model fit overall. The error correction term (COINTEQ01) is statistically significant, with a negative coefficient of -0.0897 and a p-value of 0.0132, implying that any short-term disequilibrium is corrected by 8.97% every period, returning the system to long-run equilibrium. This coefficient represents the speed of adjustment, and its statistical significance indicates that deviations from the long-run course adjust quickly.

Among the independent variables, renewable energy D(R_ENERGY) has a significant negative short-run impact, with a coefficient of -0.0118 and a p-value of 0.0012, suggesting that an increase in renewable energy consumption is associated with a short-term reduction in the dependent variable. This could imply short-term trade-offs or adjustments when shifting to renewable energy sources. Other variables such as agriculture D(AGRI), while almost significant (p-value of 0.0573), exports D(EXP01), GDP D(GDP), industry D(INDUSTRY), population (D(POP), and trade D(TRADE) do not show significant short-run effects, as their p-values are well above the typical 0.05 threshold. This suggests that, in the short term, these variables do not have a statistically measurable impact on the dependent variable, although their long-run effects could still be significant. In summary, the results suggest that while there are no broad short-run effects from most economic indicators, renewable energy plays a significant role in the short term, and the system exhibits a reasonable speed of adjustment back to equilibrium.

Table 8. Short-run panel ARDL model

Variable	Coefficient	Std. Error	t-Statistic	Prob.
COINTEQ01	-0.089684	0.035077	-2.556763	0.0132
D(AGRI)	-0.009183	0.004736	-1.939031	0.0573
D(EXP01)	-0.009665	0.008207	-1.177647	0.2437
D(GDP)	-0.001446	0.002735	-0.528948	0.5988
D(INDUSTRY)	0.002173	0.006412	0.338820	0.7359
D(POP)	-0.046571	0.051962	-0.896254	0.3738
D(R_ENERGY)	-0.011834	0.003488	-3.392911	0.0012
D(TRADE)	0.001639	0.004840	0.338716	0.7360

Sources: Authors' calculation.

4.8. Long-run coefficients for each variable

The long-run coefficients from the panel ARDL model provide crucial insights into the stable, long-term relationships between the dependent variable and the independent variables Table 9. Agriculture (AGRI) has a positive and statistically significant long-run impact with a coefficient of 0.0579 (p-value 0.0426), indicating that an increase in agricultural value-added positively affects the dependent variable in the long term. Similarly, GDP growth also shows a significant positive relationship with a coefficient of 0.0774 (p-value 0.0415), suggesting that long-term economic growth contributes to the dependent variable. In contrast, industry has a significant negative impact, with a coefficient of -0.0784 (p-value 0.0011), implying that higher industrial value-added reduces the dependent variable in the long run. This could indicate that industrial activities might have detrimental effects, such as increased environmental degradation, in the long-term context. Renewable energy consumption also demonstrates a significant negative relationship with the dependent variable, with a coefficient of -0.0236 (p-value 0.0097). This highlights the long-term trade-offs involved in the transition to renewable energy, which may lead to reductions in other economic outputs or environmental pressures. Trade exhibits a significant positive long-term effect, with a coefficient of 0.0524 (p-value 0.0231), indicating that increased trade contributes positively to the dependent variable over the long term. However, other variables, such as exports (EXP01) and population growth (POP), do not show statistically significant long-term effects, as their p-values are above 0.05.

Overall, the results reveal that agriculture, GDP growth, and trade positively contribute to long-term economic outcomes, while industry and renewable energy consumption have negative long-run effects, potentially due to environmental costs or shifts in economic structures. These findings underscore the importance of balancing industrial growth with sustainable practices and renewable energy investments in the long term.

Table 9. Long-run panel ARDL model

Variable	Coefficient	Std. Error	t-Statistic	Prob.
AGRI	0.057872	0.027925	2.072422	0.0426
EXP01	-0.026716	0.036450	-0.732949	0.4665
GDP	0.077352	0.037110	2.084408	0.0415
INDUSTRY	-0.078449	0.022819	-3.437960	0.0011
POP	-0.077405	0.090446	-0.855819	0.3956
R_ENERGY	-0.023581	0.008826	-2.671620	0.0097
TRADE	0.052352	0.022444	2.332578	0.0231

Sources: Authors' calculation

The results from the panel ARDL model show direct and sustained links between economic advancement, industrial activities, and international trade on CO_2 levels. New renewable energy technology combined with strict environmental regulations offset positive short-term emission effects from both trade and industrialization systems. Policy implementation should include short-term policies that support renewable energy investments with long-term frameworks to sustain environmental advantages as identified through the findings. Adaptation in policy creation is a necessary approach because economic factors generate changing impacts across varying periods.

4.9. Cross-Section Short-Run Coefficients

Bangladesh - Short Run Coefficients

The short-run coefficients for Bangladesh from the cross-sectional panel ARDL model provide significant insights into the immediate relationships between the variables (Table 10). The error correction term (COINTEQ01) for Bangladesh is highly significant with a large negative coefficient of -0.021841 (p-value 0.0000), indicating that short-term deviations from the long-run equilibrium are quickly corrected by 2.18% in each period, demonstrating rapid adjustment back to equilibrium. Other variables show substantial and statistically significant short-run impacts. Agriculture (D(AGRI)) exhibits a positive short-run coefficient of 9.11E-05 (p-value 0.0001), highlighting the immediate positive role of agriculture in economic adjustments. Similarly, GDP growth (D(GDP)) and industry (D(INDUSTRY)) display strong positive short-run effects with coefficients of 0.003851 and 0.010028, respectively, and p-values of 0.0000. This suggests that both economic growth and industrial activities have substantial short-term impacts on Bangladesh's economy. On the other hand, exports (D(EXP01)) and renewable energy consumption (D(R_ENERGY)) have significant negative short-run impacts, with coefficients of -0.019516 and -0.004858, respectively, both with p-values of 0.0000. These negative coefficients may reflect short-term disruptions or transitional costs related to export activities and the shift towards renewable energy sources. Furthermore, population growth (D(POP)) and trade (D(TRADE)) show significant positive effects in the short run, with coefficients of 0.016578 and 0.006919, respectively, and p-values of 0.0000. This indicates that increases in population and trade contribute positively to short-term economic adjustments in Bangladesh. The constant term (C) is also highly significant, suggesting an inherent baseline level of economic activity during the study period.

In summary, the short-run dynamics for Bangladesh show a quick adjustment to equilibrium and highlight the positive immediate contributions of agriculture, GDP growth, industry, population growth, and trade, while exports and renewable energy demonstrate negative short-term effects. These findings underscore the complexity of short-term economic adjustments in Bangladesh's economy, particularly about trade and energy transitions.

Table 10. Cross-Section Short Run for Bangladesh

Variable	Coefficient	Std. Error	t-Statistic	Prob.
COINTEQ01	-0.021841	4.99E-05	-437.9259	0.0000
D(AGRI)	9.11E-05	3.65E-06	24.95984	0.0001
D(EXP01)	-0.019516	2.37E-05	-823.9098	0.0000
D(GDP)	0.003851	3.48E-06	1105.321	0.0000
D(INDUSTRY)	0.010028	6.40E-06	1566.775	0.0000
D(POP)	0.016578	0.000293	56.60001	0.0000
D(R_ENERGY)	-0.004858	2.29E-06	-2117.726	0.0000
D(TRADE)	0.006919	3.75E-06	1843.404	0.0000
C	0.016983	0.000303	56.00643	0.0000

Sources: Authors' calculation

India - Short Run Coefficients

The short-run coefficients for India from the cross-sectional panel ARDL model provide important insights into the immediate economic dynamics (Table 11). The error correction term (COINTEQ01) is highly significant with a coefficient of -0.1081 (p-value 0.0000), indicating that deviations from the long-run equilibrium are corrected at a rate of 10.8% per period, signaling a relatively fast adjustment to equilibrium. In the short run, most variables have statistically significant impacts on India's economic adjustments. Agriculture (D(AGRI)) has a negative short-run coefficient of -0.0155 (p-value 0.0000, indicating that short-term fluctuations in the agricultural sector negatively affect economic outcomes. Similarly, exports (D(EXP01)), GDP growth (D(GDP)), and industry (D(INDUSTRY)) all exhibit negative short-run effects, with coefficients of -0.0161, -0.0029, and -0.0105, respectively, each with p-values of 0.0000. These negative relationships may reflect the transitional challenges faced by India in balancing growth, exports, and industrial activity in the short term. Renewable energy (D(R_ENERGY)) also has a significant negative short-run impact with a coefficient of -0.0153 (p-value 0.0000), which suggests that short-term increases in renewable energy consumption may have some immediate costs or inefficiencies in the economy. On the other hand, trade (D(TRADE)) has a significant positive short-run effect, with a coefficient of 0.0060 (p-value 0.0000), indicating that trade contributes positively to economic performance in the short run. However, population growth (D(POP)) shows a negative but statistically insignificant impact (coefficient -0.1496, p-value 0.1483), suggesting that population changes may not play a significant role in India's short-run economic adjustments. Finally, the constant term (C) is significant with a positive coefficient of 0.16095 (p-value 0.0032), indicating an inherent baseline level of economic activity in India during the period of analysis.

In summary, India's short-run economic adjustments are characterized by fast equilibrium correction and the significant influence of trade, while sectors like agriculture, exports, GDP growth, industry, and renewable energy face short-term challenges, reflecting the complexities of managing economic transitions.

Table 11. Cross-Section Short Run for India

Variable	Coefficient	Std. Error	t-Statistic	Prob.
COINTEQ01	-0.108141	0.002592	-41.71633	0.0000
D(AGRI)	-0.015487	6.44E-05	-240.3478	0.0000
D(EXP01)	-0.016111	0.000120	-133.7284	0.0000
D(GDP)	-0.002917	8.89E-06	-327.9643	0.0000
D(INDUSTRY)	-0.010534	7.56E-05	-139.3915	0.0000
D(POP)	-0.149625	0.077293	-1.935810	0.1483
D(R_ENERGY)	-0.015344	8.15E-05	-188.3561	0.0000
D(TRADE)	0.006025	2.44E-05	247.3440	0.0000
C	0.160950	0.018605	8.650917	0.0032

Sources: Authors' calculation.

Pakistan - Short Run Coefficients

The short-run coefficients for Pakistan from the cross-sectional panel ARDL model provide significant insights into the country's immediate economic dynamics (Table 12). The error correction term (COINTEQ01) has a coefficient of -0.1391 (p-value 0.0001), indicating that short-run deviations from the long-run equilibrium are corrected at a rate of 13.9% per period, suggesting a moderately fast adjustment back to equilibrium. In the short run, several variables exhibit statistically significant impacts. Agriculture (D(AGRI)) shows a negative short-run coefficient of -0.0122 (p-value 0.0000), indicating that short-term fluctuations in the agricultural sector negatively affect economic outcomes. Conversely, exports (D(EXP01)) have a positive and significant short-run impact, with a coefficient of 0.0066 (p-value 0.0000), suggesting that increased exports contribute positively to economic adjustments in the short term. However, GDP growth (D(GDP)) demonstrates a negative and highly significant short-run coefficient of -0.0053 (p-value 0.0000), reflecting potential short-term challenges in maintaining positive economic growth. Industry (D(INDUSTRY)) also plays a crucial positive role in short-run economic adjustments, with a coefficient of 0.0070 (p-value 0.0000), indicating that industrial activities contribute positively to economic recovery in the short run. Renewable energy (D(R_ENERGY)) shows a negative and highly significant short-run effect, with a coefficient of -0.0153 (p-value 0.0000), which could indicate transitional costs or inefficiencies associated with shifting to renewable energy sources. Similarly, trade (D(TRADE)) demonstrates a significant negative short-run impact, with a coefficient of -0.0080 (p-value 0.0000), which may highlight the short-term challenges of managing trade flows in the economy. Population growth (D(POP)) also has a significant but negative short-run impact (coefficient -0.0067, p-value 0.0005), suggesting that short-term population increases may exert pressure on economic resources. Finally, the constant term (C) is significant and positive, with a coefficient of 0.0997 (p-value 0.0165), indicating an underlying baseline level of economic activity during the study period.

In summary, Pakistan’s short-run economic dynamics are characterized by a moderate pace of equilibrium correction and significant contributions from exports and industry, while agriculture, GDP growth, renewable energy, population growth, and trade face short-term challenges, underscoring the complexity of managing economic adjustments in the country.

Table 12. Cross-Section Short Run for Pakistan

Variable	Coefficient	Std. Error	t-Statistic	Prob.
COINTEQ01	-0.139071	0.004823	-28.83198	0.0001
D(AGRI)	-0.012153	2.93E-05	-414.1293	0.0000
D(EXP01)	0.006631	2.46E-05	270.0665	0.0000
D(GDP)	-0.005273	7.36E-06	-716.1967	0.0000
D(INDUSTRY)	0.007024	2.73E-05	257.6218	0.0000
D(POP)	-0.006666	0.000415	-16.05089	0.0005
D(R_ENERGY)	-0.015298	9.40E-06	-1628.153	0.0000
D(TRADE)	-0.008026	1.17E-05	-687.4174	0.0000
C	0.099696	0.020474	4.869477	0.0165

Sources: Authors' calculation

Robustness check tests

Table 13. Model Selection Criteria

Model	LogL	AIC	BIC	HQ	Specification
1	248.590181	-4.768671*	-3.824298	-4.387844	ARDL (1 1 1 1 1 1 1 1)

Results estimated using EViews 12 (authors' analysis).

The ARDL model (1, 1, 1, 1, 1, 1, 1, 1) (Table 13) was chosen based on several criteria, including the log-likelihood value of 248.5902, and the Akaike Information Criterion, which is minimized at -4.768671. This suggests that this model provides the best fit among the competing specifications, balancing complexity and explanatory power.

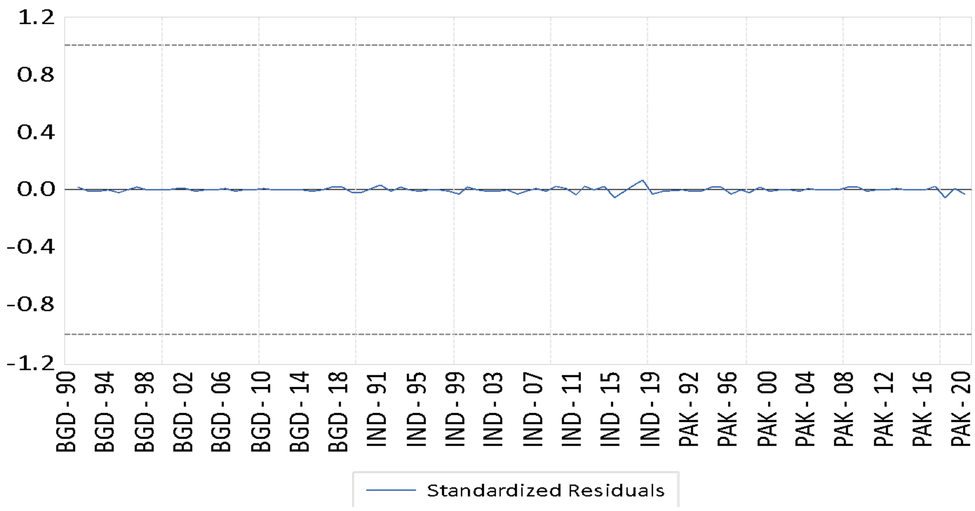

Figure 8. Standard Residual Graph
Sources: Authors' calculation

The standardized residuals graph Graph 4 indicates some variation over time, with noticeable deviations in certain years for each country, suggesting that while the model captures the broad patterns, there may be periods of volatility or external shocks affecting the residuals.

In terms of coefficient diagnostics, the elasticity of key variables reveals how they influence the dependent variable in the long run Table 14. For instance, agriculture (AGRI) has a positive impact, while industry and renewable energy show negative effects, indicating trade-offs in economic activities and sustainability efforts. Trade appears to have the most substantial positive effect on the dependent variable, highlighting the importance of international trade in driving economic growth. Overall, these robustness checks confirm the model's ability to capture key relationships between the variables but also suggest areas for further refinement, particularly regarding residual distribution and potential model improvements.

Table 14. Scaled Coefficients

Variable	Coefficient	Standardized Coefficient	Elasticity at Means
AGRI	0.057872	0.582265	1.726532
EXP01	-0.026716	-0.286608	-0.538438
GDP	0.077352	0.409199	0.566248
INDUSTRY	-0.078449	-0.743398	-2.724023
POP	-0.077405	-0.106652	-0.198003
R_ENERGY	-0.023581	-0.569764	-1.576215
TRADE	0.052352	1.155393	2.443659

Sources: Authors' calculation.

5. Discussion of Results

The results of the analysis shed significant light on the intricate relationship between economic growth, trade liberalization, industrialization, renewable energy consumption, and environmental sustainability in Bangladesh, India, and Pakistan from 1990 to 2022. The empirical findings align with the existing literature and theoretical frameworks discussed in the literature review, particularly the EKC hypothesis, PHH, and Porter Hypothesis.

5.1. Economic Growth (GDP) and CO_2 Emissions

The connection between economic growth and CO_2 emissions is marginally positive (0.07), showing that GDP growth has some effect on emissions, but other factors, such as industrial activity, trade, and energy consumption, are more important in driving emissions. This is congruent with Shahbaz *et al.* (2016), who suggested that while economic growth leads to environmental deterioration, it can be alleviated by cleaner technology at higher income levels, hence supporting the

EKC hypothesis. The Johansen-Fisher cointegration test verifies the long-term link between GDP growth and CO_2 emissions in Bangladesh, India, and Pakistan. This suggests that while short-term GDP fluctuations may not always have immediate environmental consequences, persistent economic growth has long-term repercussions for emissions levels, as shown by Stern (2004), who also discovered that EKC applies in the long run to emerging countries. The long-run ARDL results demonstrate that GDP growth has a significant positive effect on CO_2 emissions (0.0774, p-value = 0.0415). This implies that economic expansion leads to increased emissions in the long term, also validating the EKC hypothesis.

However, the short-run effects of GDP growth on emissions are not significant, suggesting that immediate economic expansion may not cause significant environmental harm unless sustained over time. In Bangladesh, GDP growth shows a significant positive short-run impact on emissions (0.003851, p-value = 0.0000), which aligns with Raihan *et al.* (2022), who highlighted that Bangladesh's rapid industrial growth has led to higher emissions, particularly as energy use remains carbon-intensive. Interestingly, India shows a negative short-run relationship between GDP and emissions (-0.002917, p-value = 0.0000), suggesting that India's recent economic growth has been accompanied by greater energy efficiency and environmental regulations. This finding aligns with the Porter Hypothesis, which posits that well-designed regulations can stimulate innovation and reduce emissions. For Pakistan, the short-run effect of GDP on emissions is negative (-0.005273, p-value = 0.0000), indicating that in the short term, GDP growth may be associated with a shift towards less energy-intensive sectors. However, over the long term, Pakistan may still struggle with rising emissions due to slow regulatory responses and dependence on fossil fuels, consistent with findings from Shahbaz *et al.* (2014).

5.2. Industrial Growth and CO_2 Emissions

Industrial growth has a moderate positive connection with CO_2 emissions (0.34), implying that increasing industrial activity leads to higher emissions. This finding is consistent with PHH, which states that developing countries with loose environmental rules may face increased industrial pollution when firms relocate from countries with stronger policies (Cole, 2004). The Johansen-Fisher test confirms the presence of a long-run relationship between industrial growth and CO_2 emissions in all three countries. This long-term link suggests that industrialization is a key driver of environmental degradation unless managed with adequate ecological regulations and clean technologies, as noted by Hettige *et al.* (2000) and Shahbaz *et al.* (2014). The long-run ARDL model finds that industrial growth has a significant negative effect on CO_2 emissions (-0.0784, p-value = 0.0011), suggesting that while industrial growth initially increases emissions, over the long term, industrial modernization, efficiency improvements, or shifts to less polluting industries may help reduce emissions. This is consistent with the Porter Hypothesis, which argues that stricter environmental standards encourage innovation and cleaner industrial processes (van Leeuwen & Mohnen, 2016).

In Bangladesh, in the short run, industrial growth significantly increases emissions (0.010028, p-value = 0.0000), reflecting the country's reliance on energy-intensive sectors such as textiles and manufacturing. This finding aligns with Alam & Butt (2021), who found that industrialization in Bangladesh has exacerbated environmental degradation due to inefficient energy use and weak environmental policies. India shows a negative short-run coefficient for industrial growth (-0.010534, p-value = 0.0000), which suggests that the country has started adopting cleaner technologies in its industries. This aligns with a national push towards renewable energy and energy efficiency, supported by studies like that by Saidi & Omri (2020), which argue that India's industrial policies are becoming more sustainable. Pakistan mirrors Bangladesh's experience, with industrial growth leading to increased short-run emissions (0.007024, p-value = 0.0000), likely due to the country's slower adoption of clean technologies and reliance on traditional energy sources, as noted in Qamri *et al.* (2022).

5.3. Trade Liberalization and CO_2 Emissions

Trade exhibits a moderate positive correlation with CO_2 emissions (0.46), indicating that increased trade is associated with higher emissions, likely due to the energy demands of export-oriented industries and transportation. This supports PHH, which posits that developing countries with weaker regulations may see an influx of polluting industries through trade liberalization, as suggested by Gill *et al.* (2018). The cointegration results confirm a long-run relationship between trade and CO_2 emissions, suggesting that while trade liberalization can initially drive economic growth and industrialization, it also leads to long-term environmental costs if not managed with proper regulations. This is consistent with findings from To *et al.* (2019), who highlighted that the environmental impact of trade liberalization depends on the regulatory framework in place. The long-run ARDL model shows a significant positive relationship between trade and CO_2 emissions (0.0524, p-value = 0.0231), indicating that trade expansion is associated with higher long-term emissions. This aligns with Liu *et al.* (2021), who found that trade liberalization can lead to increased pollution unless it is accompanied by the adoption of cleaner technologies and environmental safeguards. In Bangladesh, in the short run, trade significantly increases CO_2 emissions (0.006919, p-value = 0.0000). This result reflects the heavy reliance on export-oriented industries such as textiles, which are energy-intensive and contribute significantly to environmental degradation. The findings align with Raihan *et al.* (2022), who also observed that Bangladesh's trade-driven growth has exacerbated environmental degradation. In India, trade has a positive short-run effect on emissions (0.006025, p-value = 0.0000), which may be due to rapid industrial expansion driven by trade. However, as India increasingly adopts renewable energy and enforces environmental regulations, the long-term impact of trade may become less detrimental, consistent with Khan *et al.* (2023). In Pakistan, trade has a negative short-run impact on emissions (-0.008026, p-value = 0.0000). This is surprising, and could indicate that the immediate effect of trade liberalization involves increased efficiency in certain sectors or a temporary reduction in industrial output due to trade shocks. However, over the long term, increased trade may still contribute to higher emissions if not accompanied by environmental reform.

5.4. Renewable Energy Consumption and CO_2 Emissions

Renewable energy usage has a substantial negative connection with CO_2 emissions (-0.63), implying that increasing renewable energy use leads to decreasing emissions. This finding is consistent with previous research, such as that of Saidi and Omri (2020), which emphasizes the importance of renewable energy in minimizing the environmental impact of economic activity. The cointegration experiments indicate a long-term link between renewable energy consumption and CO_2 emissions in all three nations, implying that increasing renewable energy's proportion of the energy mix can result in long-term emission reductions. This finding aligns with Nguyen & Kakinaka (2019), who also observed long-run benefits of renewable energy adoption in reducing emissions. The ARDL model shows that renewable energy consumption has a significant negative effect on CO_2 emissions in both the short term (-0.011834, p-value = 0.0012) and long term (-0.023581, p-value = 0.0097). This underscores the importance of renewable energy as a tool for mitigating environmental degradation, consistent with the findings of Shahbaz *et al.* (2014). In Bangladesh, renewable energy has a significant short-run negative effect on emissions (-0.004858, p-value = 0.0000), suggesting that efforts to increase renewable energy adoption are already yielding environmental benefits, though there remains much room for improvement given Bangladesh's heavy reliance on fossil fuels. In India, the negative short-run impact of renewable energy on emissions is also significant (-0.015344, p-value = 0.0000). This is consistent with India's aggressive renewable energy targets and policies aimed at reducing dependence on coal and other fossil fuels (International Energy Agency, 2021). In Pakistan, renewable energy shows a strong negative short-run effect on emissions (-0.015298, p-value = 0.0000), but the overall renewable energy share remains low. Thus, while renewable energy adoption is beneficial, Pakistan needs to accelerate its energy transition to see larger long-term impacts, as suggested by Qamri *et al.* (2022).

5.5. Agriculture and Forestry Production and CO_2 Emissions

Agriculture and forestry production show a negative correlation with CO_2 emissions (-0.37). This indicates that the larger the sector's share of GDP, the lower the emissions. The negative relationship can be explained by the lower energy intensity of agriculture compared to industrial sectors. Moreover, in many cases, sustainable farming practices, such as agroforestry, can help sequester carbon and contribute to environmental sustainability. This finding aligns with Shahbaz *et al.* (2014), who also noted that agricultural sectors generally have a smaller environmental footprint compared to manufacturing or industrial sectors. The Johansen Fisher panel cointegration test confirms a long-term relationship between agriculture and forestry production and CO_2 emissions across all three countries. This long-term link suggests that shifts between agricultural production and industrialization over time have significant implications for emissions levels. In line with the EKC hypothesis, economies moving towards industrialization experience more emissions, while those retaining or increasing agricultural production may see less environmental harm. In the long run, the panel ARDL model shows a positive and significant effect of agriculture on CO_2 emissions (0.0579, p-value = 0.0426). This is somewhat surprising given the negative correlation, but it could indicate that agricultural expansion in these countries, often driven by land-use changes and deforestation, contributes to CO_2 emissions in the long term, as noted in studies like Shahbaz *et al.* (2016). In Bangladesh, in the short run, agriculture has a positive effect on emissions (9.11E-05, p-value = 0.0001). This result suggests that short-term increases in agricultural activity may be associated with emissions from agricultural practices or land-use changes, particularly where deforestation and unsustainable farming practices occur. In India, the short-run effect of agriculture is negative (-0.015487, p-value = 0.0000), indicating that agricultural activities might contribute to carbon sequestration or energy-efficient practices in the short term, which is consistent with India's efforts to promote sustainable agriculture and rural development. For Pakistan, agriculture has a negative effect on emissions in the short run (-0.012153, p-value = 0.0000). This might reflect Pakistan's dependence on less energy-intensive agricultural activities, which tend to contribute less to overall emissions.

5.6. Population Growth and CO_2 Emissions

Population growth shows a negative correlation with CO_2 emissions (-0.26), suggesting that higher population growth does not directly translate into higher emissions in South Asia. This could be because population increases are often accompanied by shifts towards more energy-efficient technologies, cleaner energy, or policies that mitigate the environmental impact of population growth. This finding is consistent with Saboori *et al.* (2012), who observed that population growth in developing economies can be offset by cleaner technologies and more sustainable practices. The cointegration test results confirm that there is a long-term relationship between population growth and CO_2 emissions in the region. While population growth can contribute to increased energy demand, the extent to which it affects emissions depends on the energy mix and industrial composition of each country. The ARDL model shows a negative long-run effect of population growth on emissions (-0.0774, p-value = 0.3956), though this result is not statistically significant. This implies that while population growth affects other factors like energy demand, it may not necessarily lead to proportional increases in emissions, especially if renewable energy is integrated into the economy. In Bangladesh, population growth has a positive and significant effect on emissions in the short run (0.016578, p-value = 0.0000). This indicates that short-term population increases may strain infrastructure and energy resources, leading to higher emissions, particularly in Bangladesh, where urbanization and industrial expansion are closely tied to population growth. In India, population growth has a negative but insignificant effect on emissions (-0.149625, p-value = 0.1483), suggesting that while the population continues to grow, the country may be implementing enough environmental policies or adopting sufficient green technologies to offset the impact of population growth on emissions. Population growth shows a negative and significant short-run effect on emissions in Pakistan (-0.006666, p-value = 0.0005). This result might reflect Pakistan's lower per capita energy consumption and ongoing energy crisis, where population growth has not yet translated into higher emissions.

5.7. Exports and CO_2 Emissions

Exports exhibit a positive correlation with CO_2 emissions (0.55), indicating that export activities are directly linked to higher emissions. This can be attributed to the fact that export-oriented sectors, especially in South Asia, tend to be energy-intensive (such as textiles, chemicals, and manufacturing), driving up emissions. This finding supports PHH, where growth in exports, especially in developing countries, leads to more pollution as countries focus on increasing industrial output to meet global demand (Gill *et al.*, 2018). The cointegration tests confirm a long-run relationship between exports and CO_2 emissions in Bangladesh, India, and Pakistan. This suggests that while short-term fluctuations in exports may not always affect emissions, long-term growth in export sectors has a lasting impact on environmental sustainability. In the long run, the ARDL model shows that exports have a negative but insignificant effect on emissions (-0.0267, p-value = 0.4665). This could indicate that while exports initially lead to higher emissions, over time, industries may adopt cleaner technologies or more energy-efficient production methods, thus reducing the negative environmental impact. In Bangladesh, exports have a negative effect on emissions in the short run (-0.019516, p-value = 0.0000). This could reflect the fact that although Bangladesh's major export industries (such as textiles) are energy-intensive, the country may be shifting towards more energy-efficient practices, supported by government initiatives aimed at improving sustainability in manufacturing sectors. In India, the short-run effect of exports is negative (-0.016111, p-value = 0.0000), suggesting that export industries might be benefiting from cleaner technologies or more efficient production processes, which help reduce their environmental footprint. This is consistent with Shahbaz *et al.* (2016), who argued that trade liberalization in India has led to both economic growth and gradual improvements in environmental standards. For Pakistan, exports have a positive and significant effect on emissions in the short run (0.006631, p-value = 0.0000). This highlights the energy-intensive nature of Pakistan’s export industries, which rely heavily on traditional energy sources, as discussed by Qamri *et al.* (2022). The country’s energy and industrial sectors have yet to transition towards cleaner practices, resulting in higher emissions as exports increase.

6. Conclusion

This study explored the complex relationships between economic growth, industrialization, trade, agriculture, population growth, renewable energy consumption, and CO_2 emissions in Bangladesh, India, and Pakistan from 1990 to 2022. The analysis provided evidence that economic activities, particularly industrial growth and trade, are significant drivers of environmental degradation, specifically CO_2 emissions, in these South Asian economies. The results align with the Environmental Kuznets Curve hypothesis and Pollution Haven Hypothesis, which suggest that economic growth initially leads to increased pollution, but improvements can occur as economies adopt cleaner technologies and implement stricter environmental regulations. Industrialization and trade liberalization, while essential for economic development, contribute significantly to short-term emissions. However, long-term trends suggest that with the right policies, including promoting renewable energy and cleaner industrial practices, these effects can be mitigated. Agricultural production and population growth showed more nuanced relationships, with agriculture having a mixed impact across countries, and population growth sometimes offset by cleaner technologies or better energy use. The analysis highlights the critical role of renewable energy in reducing emissions, both in the short and long term, across all countries. Countries like India are beginning to see the benefits of integrating renewable energy into their energy mix, which has contributed to reducing the environmental impact of economic growth.

To achieve sustainable economic growth while minimizing environmental harm, governments in South Asia—particularly Bangladesh and Pakistan—should enforce stricter industrial emissions regulations while promoting renewable energy investments through subsidies and tax incentives. Encouraging sustainable agricultural practices, such as organic farming and reforestation, can reduce emissions and boost carbon sequestration. Trade policies must incorporate environmental safeguards to support the production of low-carbon goods. Sustainable urbanization is essential for managing the environmental impact of population growth, with investments in energy-efficient infrastructure and public transport. Regional collaboration on renewable energy and environmental goals is also critical to addressing cross-border challenges.

The findings show renewable energy use produces negative CO_2 emission results, which proves that renewable energy adoption reduces environmental damage. However, more clarity is required about the processes which drive this effect. Research shows that renewable energy systems combat environmental damage caused by industrialization and market opening through both fuel conservation and enhanced energy system performance. The most significant reduction of environmental negative effects occurs in markets that have invested substantially in renewable energy facilities. The development of renewable energy in South Asia faces more hurdles from financial restrictions along with laws that are not uniform and technology restrictions. Optimizing the environmental benefits of renewable energy requires solving the mentioned obstacles by introducing specific subsidies, technology partnerships, and legislative modifications.

To better understand environmental sustainability in South Asia, future research should include indicators such as water pollution, biodiversity loss, soil degradation, deforestation, and CO_2 emissions. Sectoral studies of high-emitting industries, including textiles, chemicals, and manufacturing, are needed to evaluate pollution and sector-specific environmental policy. For sustainable growth, renewable energy regulations like feed-in tariffs and cross-border cooperation should be considered. The ecological concerns of fast urbanization in megacities like Dhaka, Mumbai, and Karachi can also inform waste management, transportation, and energy efficiency. Research on green technical innovation and financial incentives (carbon credits, green bonds) can help enhance industrial efficiency and reduce emissions. The environmental impacts of trade and investment, particularly in the context of the Pollution Haven Hypothesis and trade agreements with ecological safeguards, would help explain economic development and sustainability. Finally, comparative research on South Asian environmental policy effectiveness and international cooperation can reveal best practices for pollution reduction and low-carbon economy transition.

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