ACADEMIA International Journal for Social Sciences
Volume 4, Issue 5, 2025 ISSN-L (Online): 3006-6638

Impact of Green Energy and Technological Innovation on Climate Changes in South Asia

Ahmad Nawaz
Ahmiikhan881@gmail.com
M.Phil. Scholar at University of Southern Punjab, Multan, Pakistan

Dr. Muhammad Ali Gardezi
aligardezi@usp.edu.pk
ORCID: 0000-0002-7350-458X
Assistant Professor of Economics, University of Southern Punjab, Multan, Pakistan
Corresponding Author: * Dr. Muhammad Ali Gardezi aligardezi@usp.edu.pk

Received: 25-08-2025 **Revised:** 10-09-2025 **Accepted:** 27-09-2025 **Published:** 09-10-2025

ABSTRACT

One of the most significant threats to sustainable development is climate change and South Asia is the most exposed because it relies on fossil fuels, high economic growth, urbanization, and population increase. This paper explores how green energy and technological innovation affects greenhouse gas (GHG) emissions of 5 economies in South Asia namely India, Pakistan, Bangladesh, Nepal and Sri Lanka between 1990 and 2023. The research uses a balanced panel data and adopts the Pooled Mean Group (PMG) estimator in Autoregressive Distributed Lag (ARDL) to employ both short and long-term dynamic and equilibrium connections between the subject variables. The results show that levels of renewable energy use and technological development lead to significant lower GHG emissions long-term. Green energy helps to reduce emissions by decreasing the use of fossil fuels, whereas technological innovation helps to enhance efficiency and to promote the use of more environment-friendly ways of production. On the other hand, GDP growth, openness to trade, urbanization, and population growth put an upward pressure on emissions, especially in the short run, irrespective of the developmental and structural issues of the area. The interdependence of the three variables indicates a mutual relationship between them as evidenced by the analysis of the relationship between renewable energy and innovation and emissions through the application of the Granger causality. The findings partly confirm the hypothesis of the Environmental Kuznets Curve (EKC), which states that South Asian nations are still trapped in the pollution intensive phase of development. Also, the results correspond to the Pollution Haven Hypothesis (PHH) because an increase in industrialization caused by trade liberalization leads to environmental underdevelopment. Nevertheless, in this article we point to how implementation of renewable energy and breakthroughs in technology could reverse these trends.

Keywords: *Greenhouse Gases, Green Energy, Technological innovations and Pooled Mean group*

INTRODUCTION

Climate change has become one of the most significant issues of the 21 st century to humankind as it is a threat to the basic economic, environmental, and social sustainability. The Intergovernmental Panel on Climate Change (IPCC) has several times demanded that the global greenhouse gas (GHG) emissions must be swiftly reduced in the event that the world wishes to limit the global temperature rise to less than 1.5degC without causing irreversible alterations to ecosystems, human health and livelihood (Musah et al., 2023). The impact of climate change is particularly dangerous to developing economies such as South Asia due to high dependence on fossil fuels, abject poverty, low institutional capacity and adaptation plans (Z. Li et al., 2022).

This is sweeping urbanization, industrialization and globalization in the region of South Asia, which has a population of close to a quarter of the global population and has added pressure on the environment. The regional countries India, Pakistan, Bangladesh, Nepal and Sri Lanka have pursued growth policies that are premised on high utilization of the traditional forms of energy, namely, coal, oil and natural gas (Behera and Dash, 2017). Even though these sources of energy have contributed to industrial growth, transport infrastructure, and rising standards of living, it is the same sources that have contributed to GHG emission rise, air quality degradation, deforestation, and the rise of climate catastrophes, such as floods, droughts, and heat waves. As an illustration, the levels of air pollution in major South-Asian cities are currently ranked among the highest in the world and rising temperatures threaten the agricultural output and food security. The importance of finding sustainable development avenues increases with the trends further (Akbar et al., 2020).

Green energy introduction and technological innovation promotion are the two measures in this context that have become most applicable in stopping climate change. The term, which denotes renewable and clean energy sources, such as solar, wind, hydro, biomass and geothermal energy, is green energy. These sources can be used to replace fossil fuels as they offer sources of energy that are low- or zero-emission energy sources (van Vuuren et al., 2017). The potential of the renewable energy in South Asia is immense: the land is fortunate to have adequate amounts of sunlight, wind areas, hydro power and biomass supplies. Already, such countries as India and Pakistan have launched aggressive renewable energy developments, including large-scale solar parks and wind farms, but the portion of renewables in the energy mix of the region is minimal relative to the fossil fuels (Y. Chen et al., 2024). Thus, the revitalization of renewable energy infrastructure and making it affordable and available to all are the key factors in decarbonizing the region of carbon emissions.

Technological innovation plays the complementary role in addition to a more significant role. Advanced energy efficiency, digital technologies, smart grids, electric vehicles, and clean production processes are new technologies that can drastically decrease the intensity of energy and the number of emissions (L. Zhang et al., 2023). As an example, energy-efficient appliances and industrial machinery would reduce the quantity of energy required to manufacture the products, and digitalization would allow developing smarter energy management systems. Moreover, the transfer of technology between the developed and the developing economies can provide a possibility of South Asia to jump to cleaner forms of technology without going through some of the most devastating stages of industrialization which defined the models of development in the past (Raihan, 2023). Nonetheless, despite such prospects, South Asia remains underperforming in research and development (R&D) expenditure, patent applications and transfer of innovative technologies to the industries.

The problem is the tradeoff between economic growth and environmental sustainability. On one hand, South Asian economies must find ways to grow at high rates to reduce poverty, generate jobs and improve living standards (Acheampong et al., 2021). On the other hand, this growth has historically been paid at the cost of degraded ecosystems, since industrialization and urbanization continue to be tightly linked to the use of fossil fuel. The Environmental Kuznets Curve (EKC) hypothesis proposes that environmental degradation first rises with rising income, and then, once countries become wealthy enough, starts to fall as countries transition to cleaner technologies. However, if and when South Asian economies have arrived or are near a such tipping point is an open question. High emission levels persist despite the recent economic growth, which indicates that economic growth in the region is still at the environmentally degrading stage of the EKC (Leal & Cardoso Marques, 2019).

Against this background, it is clear that the adoption of green energies and technological innovation are not optional but a must for South Asia to ensure sustainable development. These not only decrease emissions, but also offer new opportunities for new industry, green jobs, and long-term energy security.

They can help decouple economic growth from environmental degradation and enable countries to pursue a development path that is inclusive, resilient and ecologically responsible (Filippidis et al., 2021). The big question is why, despite their potential, both renewable energy and innovation are hindered by high upfront costs, poor institutional structures, poor infrastructure, shortage of skilled manpower and poor public awareness.

Thus, the effect of green energy and technological innovation on climate change in South Asia is an opportune and critical subject to be researched. This paper provides empirical data of how these factors interact with greenhouse emissions, and factors such as economy, demographic and policy related factors are controlled. These types of studies are very important in educating policy-makers on how to ensure that growth and environmental sustainability can co-exist. By pinpointing the determinants of emissions and estimating the potential of renewable energies and of innovation, the study provides useful input to regional cooperation, policy reforms and future development strategies.

LITERATURE REVIEW

The interaction between energy use, technological transformation and environmental sustainability has become one of the most vigorously researched strands of economics and policy research in the last three decades. The rapid pace of industrialization, globalization and demographic change has placed unprecedented pressure on ecosystems, while the increased threat of climate change has made the quest for sustainable models of growth urgent and unavoidable. There is now a consensus among scholars, policymakers, and international organizations that economic development cannot be achieved without the simultaneous efforts to reduce greenhouse gas emissions and to adapt to a climate where the climate changes (IPCC, 2021).

Shahbaz et al. (2013) found that the carbon emissions in Pakistan substantially increased along with its GDP growth in both the short and long run, thus supporting the EKC only in part. Similarly, Javid and Sharif (2016) found that industrial development in India and Bangladesh were strongly correlated with emissions, mainly by coal use. These results point to the dilemma between development and environmental sustainability in South Asia.

The other key driver of emissions is urbanization. As populations move to cities, housing, transportation, electricity, and infrastructure needs expand. There are works which have demonstrated that urbanization tends to increase carbon emissions, especially in developing regions where urban planning and green infrastructure are not well managed (Poumanyvong & Kaneko, 2010).

In South Asia, rapid urbanization has fueled growth in energy demand and pollution levels. For instance, Ahmed et al. (2017) analysed that urbanisation in India substantially contributed to carbon emission, especially due to growth in transport and construction sectors. Similar trends have been seen in Pakistan and Bangladesh, where urbanization is accompanied by sprawl, congestion and inefficient energy use.

Openness to trade can influence emissions in a number of ways. On the one hand, globalization may raise emissions by promoting production growth of energy-intensive sectors in accordance with the PHH. On the other hand, trade can induce technology transfer, producing cleaner production. Antweiler et al. (2001) characterize this double impact as the "scale, composition and technique" effects of trade. There is evidence from South Asia that tends to corroborate the pollution haven hypothesis. Shahbaz et al. (2017) show that trade openness in South Asia substantially increased emissions as exports are still concentrated in energy intensive industries in the region. However, there are also studies which document the potential of trade for improving energy efficiency through access to cleaner technologies and capital goods (Frankel & Rose, 2005).

The transition to renewable or green energy has always been viewed as one of the most efficient methods of reducing the emission of greenhouse gases and curbing climate change. These renewable energy sources such as solar, wind, hydropower, biomass and geothermal all emit little or no direct emissions, and are the backbone of any sustainable energy system, unlike fossil fuels. In a huge literature, it has been established that the adoption of renewable energy has environmental implications globally. An example of this is a study by AperGIS and Payne (2010) that shows that, in OECD countries there was a significantly important long-run relationship between renewable energy consumption and CO2 emissions, with renewables proving to have a strong decisive influence on emissions abatement. Likewise, the research of Sadorsky (2009), using the data of G7 countries, revealed that there is a significant mitigating effect of emissions by the consumption of renewable energies even after factoring in GDP and trade. Extending this evidence to emerging markets, Bilgili et al. (2016) found that renewable energy use in 17 developing countries contributed substantially to reduce CO2 emissions, lending further credence to the case that renewables are critical for the transition to sustainable development. Destek and Sinha (2020) confirmed this trend for OECD countries, and indicated that renewable energy reduces the environmental degradation in the short and long run.

Each source of renewable energy makes a different contribution to reducing emissions. Solar energy especially has great potential in areas of the world with a high solar resource such as South Asia, where solar photovoltaics can substantially decrease the reliance on coal and oil for electricity production (REN21, 2021). Wind energy has also proven successful in areas with steady wind flows, as we have seen in Denmark's successful energy transition (Lund 2007). While historically one of the most widely used renewable sources, hydropower is able to continue to deliver stability and scale in the face of concern about ecological effects, such as river disruption. Biomass and Geothermal energy are also options, albeit less developed, especially where biomass is used sustainably to replace conventional wood burning and decrease emissions resulting from deforestation. As such, solar and wind seem particularly well-suited to South Asia from a global evidence base, due to the region's geographic and climatic conditions.

Along with renewable energy, another key determinant of environmental sustainability is technological innovation. Innovation allows energy and resources to be applied more efficiently and thus decreases the ecological intensity of economic activity. We also have strong evidence from around the world that technological innovation is a powerful means of reducing emissions. Indicating that environmentally-friendly innovation played an important role in emission reductions, Popp (2002) used cross-country patent data. Costantini and Mazzanti (2012) went on to state that eco-innovation is essential to reconciling growth with sustainability because it will not only reduce emissions but also spur the growth of green industries and jobs. More recently, the use of digital technologies (artificial intelligence, big data, Internet of Things (IoT)) increasingly used to optimize energy systems, reduce waste and track environmental performance in real time have been highlighted by researchers (George et al., 2021).

Technological innovation increases energy efficiency by lowering the amount of energy required to produce a given amount of output. From energy-efficient appliances to smart building materials, industrial machinery advancements are contributing to a reduction in overall energy demand. There is ample empirical evidence of this effect. Zhang, Shahbaz and Binh (2017) concluded that technological advancement in BRICS countries has resulted in considerably lower energy intensity and emissions. We also demonstrate that, especially in developing economies, in which industries are characterized by outdated and inefficient technologies, the introduction of modern production systems can have significant positive environmental impacts.

More innovations have changed the process of production in industries with the help of clean technologies. Carbon capture and storage (CCS), circular economy and waste-to-energy are examples of how innovation can help reduce emissions at an industrial scale. Porter and van der Linde (1995) had argued that stringent environmental regulations can in fact be an innovation stimulus that enhances competitiveness, and this hypothesis has subsequently been confirmed by evidence that firms often experience long-run productivity benefits from implementing cleaner technologies.

In the context of South Asia, however, technological innovation is still restricted. R&D expenditure is less than 1% GDP in most countries, in contrast to over 2% in developed economies (UNESCO, 2020). However, advancement can be seen in some areas. India has pioneered in digital technologies, IT and renewable integration. Pakistan has created small-scale solutions like solar-powered irrigation and energy-efficient appliances. Bangladesh has led the way in low cost solar home systems, while Sri Lanka has experimented with biomass gasification. Empirical studies support the advantages of innovation in the region. Khan et al. (2020) found that technological innovation in South Asia is one of the main contributors to emission reduction, but the magnitude of the contribution depends on the country. Furthermore, Ullah et al. (2021) proposed that synergy exists between innovation and the adoption of renewable energy in their findings, which enhances the emission reduction. Despite these advantages, the lack of investment, poor intellectual property rights regime, brain drain of the skilled manpower, and limited partnership between research institutions and industry are hampering the progress.

Overall, the literature suggests that both renewable energy and technological innovation play an important role in reducing emissions and contributing to sustainability in South Asia. However, they only have a chance to succeed if they can overcome financial, institutional and policy-related barriers. The opportunities exist due to the decreasing technology costs, increasing international backing of clean energy and a chance of South Asia to jump to cleaner technologies. It is required to have a combined strategy of deploying renewable energy that also extends to the innovation ecosystems to address climate change and to ensure both economic growth at the same time.

Despite the increasing pace of research on renewable energy, innovation in technologies, and climate change, there are still some key gaps, especially in the case of South Asia. First, the literature to date is concentrated on developed countries or large emerging economies like China, with South Asia under-represented despite being a climate-vulnerable region with rapidly increasing emissions. Second, most studies in the region have focused on renewable energy and growth, paying less attention to the integrated role between technological innovation and other socio-economic factors like trade openness, urbanization and population growth. Third, existing studies are time-series cross-sectional studies at the country level that cannot reflect the heterogeneity of South Asia as a region. Long-run, panel-based research that includes cross country variation and dynamic effects are not common.

MODEL, DATA AND METHODOLOGY

It is the methodological framework of the current study that allows the empirical investigation of the effects of green energy and technological innovation on climate change in South Asia. This section explains the econometric model, the variables to be used in the analysis, the source of data, and estimation methods. The main analytical instrument used in this paper is the Pooled Mean Group (PMG) estimator in the Autoregressive Distributed Lag (ARDL) panel model, which best befits the investigation of both the short-run and the long-run dynamics at the country level. Through this approach, the proposed study aims to generate credible and policy-providing research findings on the impacts of renewable energy consumption and technological innovation in the area in terms of greenhouse gas emissions. The Empirical Model The overall model of this paper is to describe the determinants of greenhouse gas (GHG) emissions in relation to green energy, technological innovation and the choice of social-economic variables. The functional form in the base state is the following:

$$GHG_{it} = f(GE_{it}, TI_{it}, GGP_{it}, URB_{it}, TO_{it}, POP_{it}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where GHG_{it} is the greenhouse gas emission in country i at time t, GE it is the green energy, Technology innovation TI it, GDP it is GDP per capita, Urbanization URB it, Trade openness TO it and Population growth POP it. In order to estimate this relationship, the study uses a panel ARDL model. The overall ARDL(p,q,...) model may be expressed as:

$$GHG_{it} = \beta_1 + \beta_2 GHG_{it-1} + \beta_3 GE_{it} + \beta_4 TI_{it} + \beta_5 GDP_{it} + \beta_6 URB_{it} + \beta_7 TO_{it} + \beta_8 POP_{it} + \mu_{it} \ldots\ldots (2)$$

This specification enables the study to capture the short-run country specific dynamics as well as the usual long-run equilibrium relationships among South Asia.

Description of Variables

Table 1. Description of Variables

Abbreviations	Variable	Description	Source
GHG	Greenhouse Gases	Total greenhouse gas emissions (Mt CO2e)	World development indicator (WDI)
GE	Green Energy	Renewable energy consumption (% of total final energy consumption)	World development indicator (WDI)
TI	Technological innovation	Patent applications, residents	World development indicator (WDI)
GDP	Gross Domestic Product	Constant 2015 US$ as a proxy of gross domestic product	World development indicator (WDI)
TO	Trade openness	Import + Exports of goods and services (constant 2015 US$) divided by GDP deflator	World development indicator (WDI)
URB	Urbanization	Urban population (% of total population)	World development indicator (WDI)
POP	Population Growth	Population growth (annual %)	World development indicator (WDI)

RESULTS AND DISCUSSIONS

This section describes and discusses the empirical findings of the research on Impact of Green Energy and Technological Innovation on Climate Change in South Asia. The analysis is derived from econometric estimates performed with a panel data across the selected countries in South Asia on the relation between greenhouse gas emissions, adoption of renewable energy, technological advancements, and other socio-economic variables. Results are interpreted with respect to the research objectives, showing the degree to which green energy and technological innovation contribute to climate change mitigation after controlling for GDP per capita, urbanization, trade openness, and population growth. The discussion also links findings to the literature, pointing out similarities, differences and new findings emerging from the South Asian context.

Table 2. Descriptive Statistics

	LGHGS	LGE	LTI	LGDPC	LURB	LTO	LPOP
Mean	5.421782	3.958860	4.894844	6.823639	3.242257	20.58192	0.365838
Median	5.500928	3.915018	4.085941	6.888515	3.370779	20.69900	0.488164
Maximum	8.196736	4.554929	10.40949	7.712584	3.700635	22.90083	1.206883
Minimum	2.570117	3.203153	1.098612	6.046721	2.180869	18.05967	-1.612493
Std. Dev.	1.654470	0.359014	2.397372	0.424206	0.368787	1.567919	0.558059
Skewness	-0.115834	0.078647	0.855341	0.017690	-1.111743	-0.196631	-1.319098
Kurtosis	2.050746	2.183975	2.469359	1.955687	3.373987	1.791596	5.248804
Jarque-Bera	5.330700	3.856060	17.91138	6.096113	28.38433	9.016508	67.09603
Probability	0.069575	0.145434	0.000129	0.047451	0.000001	0.011018	0.000000
Sum	726.5189	530.4873	655.9090	914.3676	434.4624	2757.978	49.02231
Sum Sq. Dev.	364.0570	17.14250	764.4034	23.93350	18.08847	326.9632	41.42012
Obs	134	134	134	134	134	134	134

The descriptive statistics give an account of the variables used in the study with the dependent variable being log of greenhouse gas emissions (LGHGS) and the independent variables such as log of green electricity (LGE), technological innovations (LTI), GDP per capita (LGDPC), urbanization (LURB), trade openness (LTO) and population (LPOP). The central tendency of data is reflected in the mean values, where LGHGS is approximately 5.42, i.e. moderate greenhouse gas emissions in the panel, and LGE and LTI are 3.95 and 4.89 respectively, i.e. fairly harmonious adoption of green energy and technological innovation. A higher LGDPC mean (6.82) is reflecting the economic progress, while a lower LURB mean (3.24) is reflecting an increasing urbanization level. LTO has the largest mean of 20.58, which reflects high trade exposure, and LPOP averages 0.36, which reflects relatively smaller log population growth. The means and medians are close to each other, with the variables being less skewed in most cases, with the exception of LTI and LPOP.

Table 3. Correlation Analysis

	LGHGS	LGE	LTI	LGDPC	LURB	LTO	LPOP
LGHGS	1						
LGE	-0.8140	1					
LTI	-0.9172	-0.6394	1				
LGDPC	0.60902	-0.7762	0.4882	1			
LURB	0.7956	-0.8860	0.5430	0.8037	1		
LTO	0.9071	-0.7664	0.8042	0.5510	0.7696	1	
LPOP	0.1633	0.0122	0.0392	-0.2178	0.0495	0.2996	1

The correlation matrix gives useful information concerning the relationships among the variables in the model. The dependent variable LGHGS (greenhouse gas emissions) is significantly negative correlated with LGE (-0.8140) and LTI (-0.9172) which indicates that the greener energy usage and the higher technological innovations, the lower emissions are caused. This matches the theoretical prediction that cleaner energy and technological change have a positive impact on environmental quality. LGHS is on the other hand strongly and positively correlated with LTO (0.9071) and LURB (0.7956) which suggests that increasing trade openness and rapid urbanization are associated with higher emissions, presumably due to industrialization, energy demand and growth of carbon-intensive activities. Likewise, GDP per capita

(LGDPC) is moderately positively correlated (0.6090), which is associated with environmental pressures of economic growth. Population (LPOP) has a weak positive correlation (0.1633) with emissions, which implies that population growth alone is not a major driving factor behind emissions when compared to structural factors such as trade or energy use.

Table 4. Details of Panel Unit Root Test

Variables	Results of ADF		Results of PP		
	Level	1st difference	level	1st difference	Decision
LGHGS	0.0001	0.0000	0.0000	0.0000	**1(0)**
LGE	0.8316	0.0012	0.9971	0.0000	**1(1)**
LTI	0.0429	0.0000	0.0001	0.0000	**1(0)**
LGDPC	1.0000	0.0000	1.0000	0.0000	**1(1)**
LURB	0.9126	0.0004	1.0000	0.0007	**1(1)**
LTO	0.4925	0.0000	0.5831	0.0000	**1(1)**
LPOP	0.6902	0.0000	0.9531	0.0000	**1(1)**

The Panel unit root test results (Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP)) give evidence on the stationarity of the used variables in the model. For panel time-series analysis, stationarity is of fundamental importance in order to avoid spurious regressions and derivable long-run estimations. The results show that the dependent variable, LGHGS (log of greenhouse gas emissions) is stationary at level [I(0)], since both ADF and PP tests reject the null hypothesis of the unit root with p-value values that are nearest to zero. Similarly, LTI (log of technological innovations) also is demonstrated to be stationary at level under both test procedures, so it is integrated of order zero. This means that greenhouse gas emissions and technology growth are time-invariant with stable mean-reversion.

Table 5. Results of Panel co-integration

Kao Residual Cointegration Test		
	t-Statistic	**Prob.**
ADF	-3.305072	0.0005
Residual variance	0.001334	
HAC variance	0.002971	

The Kao Residual Cointegration Test is used to determine whether or not a long-run equilibrium relationship among the variables in the model exists. The null hypothesis of the panel test is that no cointegration exists among the variables of the panel and the alternative hypothesis is that cointegration exists. The ADF t-statistic value is -3.305072 with the corresponding probability value of 0.0005. Since the probability value is well less than the 1% significance level, the null hypothesis of no cointegration is strongly rejected. This implies that the variables in the study are cointegrated, suggesting a long-run equilibrium relationship among GHGS (LGHS), on the one hand, and green energy (LGE), technological innovation (LTI), GDP per capita (LGDPC), urbanization (LURB), trade openness (LTO) and population (LPOP), on the other hand.

Table 6. Long run results of PMG/ARDL

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LGE	-0.511250	0.015935	-32.08363	0.0000
LTI	-0.864108	0.251599	-;3.434469	0.0012
LGDPC	0.549229	0.025605	21.45037	0.0000
LURB	0.613595	0.334227	1.835862	0.0705
LTO	0.019435	0.000135	144.1968	0.0000
LPOP	0.159354	0.000647	246.4432	0.0000

The long-run PMG/ARDL estimation gives valuable insight into dynamic relationship between economic, technological and demographic variables and greenhouse gas (GHG) emissions of South Asia. The coefficient of green energy (LGE) is negative (-0.511) and highly significant and this show that increased share of renewable energy plays a significant role in reducing the emission. In particular, the utilization of green energy is observed to reduce the emissions by about 0.51 percent of every 1 percent of an increase in the green energy utilization thus justifying the importance of clean energy as a viable means of sustainability. This outcome can be aligned with Sadorsky (2009) and Bilgili et al. (2016) who concentrate on the effects of mitigating climate change by implementing renewable energy. In a like manner, technological innovations (LTI) have a negative and significant coefficient (-0.864) that means that technological advancement influences even more the reduction of emissions through diffusion of energy efficiency, cleaner production, and green technology. This agrees with the position of Zhang et al. (2017) and Khan et al. (2020), that innovation is the essence of sustainable growth. However, the coefficient of GDP per capita (LGDPC) is positive and significant (0.549), which implies that economic growth has a positive effect on GHG emissions by 0.55% in response to a 1% increase in income level, thus implying that the scale effect dominates in developing economies. Hence, this result is consistent with the Environmental Kuznets Curve (EKC) hypothesis in its first stage, where economic growth is associated with environmental degradation (Shahbaz et al., 2013; Al-Mulali & Ozturk, 2016; Shaheen et al., 2025).

The coefficient of urbanization (LURB) also has a positive coefficient (0.614), albeit marginally significant, indicating that rapid urbanization has a positive influence on emissions through greater energy demand for transport, housing, and infrastructure. This is in accord with Poumanyvong & Kaneko (2010), who also observed that urbanization of developing countries is emission-intensive. Openness to trade (LTO) has a positive but relatively smaller coefficient (0.019) indicating that openness to trade leads to environmental degradation, confirming the "pollution haven" hypothesis (Cole, 2004; Shahbaz et al., 2017; Ali Gardezi & Samar Abbas, 2021; Ghaffar & Ali Gardezi, 2024; Kiran & Gardezi, 2024)) as South Asia's exports are concentrated in energy-intensive sectors. Population (LPOP) has a strong positive coefficient (0.159) suggesting that demographic pressure has a positive impact on emissions by increasing energy demand, transport and industrial demand, consistent with Dietz and Rosa (1997) and O'Neill et al. (2010). Overall, the results point to a double-edged sword: on the one hand, green energy adoption and technological change exert a determinative impact on emissions reductions; on the other hand, economic growth, urbanization, openness to trade, and population increase substantially degrade the environment. These results suggest that South Asia confronts trade-off between economic growth and environmental sustainability, and thus needs to emphasize policies that promote renewable energy investments, technologies, sustainable urbanization, and population management policies for sustainable growth over the long term.

Table 7. Short run results of PMG/ARDL

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
COINTEQ01	-0.174188	0.065908	-2.642904	0.0101
LGE	-0.777973	0.321109	-2.422768	0.0179
LTI	-0.518484	0.192531	-2.692993	0.0100
LGDPC	0.353326	0.130621	2.704965	0.0100
LURB	0.526045	0.294350	1.787143	0.0781
LTO	0.260878	0.067278	3.877615	0.0003
LPOP	0.079111	0.045957	1.721419	0.0895
C	-4.436771	2.175011	-2.039884	0.0488

This short-run PMG/ARDL estimation is insightful in the immediate and transitional effects of economic, technological and demographic variables on greenhouse gas (GHG) emissions in South Asia, which supplements the long-run results. The error correction term (COINTEQ01) is negative (-0.174) and statistically significant at 1% level verifying convergence toward the long-run equilibrium. Specifically, it implies that about 17.4% of short-run disequilibrium is recovered in each period, which implies that convergence to long-run equilibrium is gradual but substantial. In terms of explanatory variables, green energy (LGE) has a significant negative effect (-0.778), which indicates that in the short term, an increase of 1% of renewable energy consumption decreases GHG emissions by about 0.78%. This further implies that clean energy transition has an immediate abatement (mitigating) effect on emissions, which is in line with Sadorsky (2009) and Bilgili et al. (2016), who find that renewable energy reduces environmental degradation even in the short run. Technological innovations (LTI) also reduce emissions considerably (-0.518), validating the fact that technological progress (energy-efficient machinery, environmentally-friendly production, digital technologies, etc.) has an almost immediate impact on environmental quality. This is consistent with the empirical evidence found in Zhang et al. (2017) and Khan et al. (2020) that innovation lowers energy intensity and emissions in the short and long run. On the other hand, the coefficient of GDP per capita (LGDPC) is also positive and significant (0.353), that means economic growth has an initial positive impact on emissions, which means the scale effect of industrialization and fossil fuel consumption in the growth process. Concerning urbanization (LURB), the positive (0.526) but marginal significance indicates that rapid urbanization leads to higher emissions in the short-run due to the development of infrastructure, transport, and energy demand as found in Poumanyvong & Kaneko (2010).

Trade openness (LTO) has a significant and positive coefficient (0.261), which suggests that an expanding trade activity deepen the emissions in the short run, which confirms the "pollution haven" effect found in developing economies (Cole, 2004; Shahbaz et al., 2017; Rasheed et al., 2025; Saeed & Gardezi, 2025). Population growth (LPOP) also has a weakly positive impact (0.079), significant at the 10% level, indicating that demographic pressures are also related to short-run environmental degradation through increased energy use consumption and resource use, corroborating Dietz & Rosa (1997). Lastly, C is negative and significant - indicating unobserved effects which may mitigate emissions in the short term, potentially due to structural policies or seasonal effects. Overall, the short-run dynamics show that while green energy and technological innovation offer short-term environmental co-benefits, growth, trade and urbanization are impositions on emissions, suggesting the need for interventions in the short term to complement long-run sustainability solutions.

Table 8. Results of Diagnostic Tests

R^2	0.7543	**Bruch Pagon Hetero Test**	2.0234 (0.1136)
Adj R-squared	0.7586	**Ramsey RESET Test**	1.1865 (0.2385)
Durbin-Watson statistics	2.0675	**Jarque-Bera**	1.4986 (0.4875)

The probability values are in brackets.

The diagnostic statistics indicate the robustness, reliability and overall goodness of fit of the estimated PMG/ARDL model. The R2=0.7543 and adjusted R2=0.7586 suggest that about 75-76% of the variation of greenhouse gas emissions can be explained by the explanatory variables, which is high explanatory power for a type of panel model. The heteroskedasticity test of Breusch-Pagan gives a statistic of 2.0234 (p-value = 0.1136), which is higher than the significance level of 5%, which means that the null hypothesis of homoskedasticity cannot be rejected. Thus, there is no indication of heteroskedasticity in the residuals and thus the estimated coefficients are efficient. The value of the Ramsey RESET test statistic of 1.1865 with the probability of 0.2385 shows that there is no functional form misspecification which means that the model is correct and no important nonlinear relationships are missing. Moreover, the Durbin-Watson statistic is 2.0675 which is very close to the ideal benchmark of 2 showing that any potential autocorrelation in the residuals has been ruled out which is vital to obtain unbiased and robust estimation in time-series and panel data models. Also, Jarque-Bera test is 1.4986, with a p-value of 0.4875, which indicates that the residuals are normally distributed and therefore, the assumptions of classical regression analysis are satisfied. Overall, these diagnostic tests indicate that the model is well-specified and free from serious econometric problems, such as heteroskedasticity, autocorrelation or non-normal residuals. Thus the estimated short run and long run coefficients can be said to be reliable for policy interpretation purposes. These diagnostic results in addition to confirming the robustness of the PMG/ARDL framework enhance the reliability of the findings that green energy adoption and technological innovations reduce emissions, and economic growth, urbanization, trade openness, and population growth increase environmental degradation in South Asia. Hence the overall model satisfies key econometric tests to enable both the statistical and economic conclusions that are derived from the analysis to be valid and appropriate for policy development.

Table 9. Pairwise Granger Causality

Null Hypothesis:	F-Statistic	Prob.
LGE does not Granger Cause LGHGS	3.61889	0.0297
LGHGS does not Granger Cause LGE	2.79461	0.0651
LTI does not Granger Cause LGHGS	3.96452	0.0215
LGHGS does not Granger Cause LTI	2.70679	0.0707
LGDPC does not Granger Cause LGHGS	4.46349	0.0134
LGHGS does not Granger Cause LGDPC	4.16047	0.0178
LURB does not Granger Cause LGHGS	2.84821	0.0618
LGHGS does not Granger Cause LURB	2.45629	0.0901

LTO does not Granger Cause LGHGS	3.87657	0.0234
LGHGS does not Granger Cause LTO	5.54089	0.0050
LPOP does not Granger Cause LGHGS	2.50135	0.0861
LGHGS does not Granger Cause LPOP	3.60428	0.0301

The pairwise Granger causality test results are rich in information on the direction of the relationships between GHG emissions (LGHGS) and explanatory variables green energy (LGE), technological innovation (LTI), GDP per capita (LGDPC), urbanization (LURB), trade openness (LTO) and population (LPOP) in South Asia. The results indicate both evidence of unidirectional and bidirectional causality. First, LGE Granger causes LGHGS at the 5% level ($p = 0.0297$) and the reverse causality is marginally significant at the 10% level ($p = 0.0651$), indicating the presence of a largely unidirectional causality from LGE to emissions. This demonstrates that renewable energy penetration provides a large contribution to emissions mitigation, which is consistent with the hypothesis that environmental impacts are more strongly driven by clean energy sources than by emissions driving clean energy policy. A similar relationship is observed for technological innovation (LTI), which Granger causes LGHGS ($p = 0.0215$) while the other relationship is only weakly significant ($p = 0.0707$). This indicates that technological change is an important contributor to emission abatement, as will be shown by Zhang et al. (2017), whereas feedback effects are smaller. In contrast, exposure to LGHGS is bidirectional with GDP per capita (LGDPC) as both directions are significant at the 5%, suggesting that economic growth leads emissions and, at the same time, increased emissions have a direct impact on growth-related policies, a phenomenon largely discussed in the EKC framework (Shahbaz et al., 2013). For the variable urbanization (LURB), the effect is only marginally significant in the two directions, indicating weak evidence of two-way causality, which may reflect the effects of urbanization on emissions through infrastructure and energy use as well as the indirect effects of increasing emissions on urban planning. For trade openness (LTO) and LGHGS, a stronger bidirectional causality sign is found with both directions significant ($p = 0.0234$ and $p = 0.0050$, respectively), confirming that trade expansion leads to higher emissions and degradation leads to the trade related policies, as supported by the "pollution haven" and "scale effect" hypotheses. Finally, population (LPOP) has mixed results, with LGHGS Granger causing LPOP ($p = 0.0301$) but the reverse just barely significant ($p = 0.0861$), which would mean the feedback of emissions (demographic trends through its effects on migration and health implications etc.) is greater than the effect of population directly driving short-run emissions. In general, the findings of our Granger causality suggest that green energy and technological innovations matter as determinants of emission reduction, but GDP and trade openness are strongly related to environmental degradation regardless, but population and urbanization are less than significant and bidirectionality causal variables. These results indicate that energy and technology policies should regulate emissions and at the same time take into consideration the development, trade, and demographic aspects of South Asian economies.

CONCLUSION, RECOMMENDATIONS AND POLICY IMPLICATIONS

The objective of this paper was to empirically investigate the relationship between Green Energy and Technological Innovation and Climate Change in South Asia by using panel econometric methodology. The findings provide credible indication that implementation of renewable energy and technological advancement are viable mechanisms through which greenhouse gases since their emission in the area can be minimized. On both short and long-term basis, it was observed that green energy and innovation could contribute significantly to lowering emissions, and therefore, it is important to note that it can significantly help in attaining environmental sustainability. Simultaneously, the emissions were indicated to be positively correlated to economic development, urbanization, openness to trade and population increase, which implies that South Asian economies are still mostly dependent on the carbon-intensive development patterns. The results confirm that there is long run cointegration of variables that show the economic and environmental processes are long run cointegrated. The analysis of Granger causality also showed that green energy and technological innovation are active contributors of emission reduction and GDP per capita and trade openness have a two way relationship with emission and embody trade-off between development and sustainability.

These findings, on the basis of which, result in certain significant proposals. South Asian economies should also increase the renewable energy infrastructure significantly by investing in solar, wind, hydro and biomass and providing subsidies and incentives to the participation of the private sector. Simultaneously, technological innovation should be regarded as a climate strategy pillar. More public and private research and development, technology transfers and university-industry partnerships would accelerate the diffusion of cleaner and more efficient technologies. Economic growth should also be low-carbon as required. Carbon pricing, emission standards and green industrial policies must include an environmentally sustainable development agenda in national development plans. Moreover, sustainable urban planning solutions such as energy-efficient housing, mass transportation, and intelligent infrastructure should foster urbanization in order to reduce the level of emissions by the rapidly developing cities.

Policy implications of this study are bountiful and urgent. South Asian energy policies ought to undergo radical change by abandoning the reliance on fossil fuel and greatly focusing on renewable energy. Technological innovation is no longer to be regarded as a driver of the economy only, but as a valuable instrument of climate change mitigation. By embedding into the policy makers repertoires such tools as carbon taxes, cap-and-trade schemes, and environmental impact analysis, we need to make the externalities of the economic activity internal. The city governance mechanisms should be altered to accommodate sustainable cities and the trade policies should be in tandem to be able to strike a balance between competitiveness and environmental protection. In addition, the policies of population management and human development should be discussed as the key components of climate change policy because the improvement of education, health and empowerment may indirectly cause the decrease of emissions.

FUTURE RESEARCH DIRECTIONS

Several potential future research areas do still exist which remain notwithstanding the strong insight provided in this study. To begin with country-level panel data may be complemented with sectoral or firm level data to provide more information on which industries or sectors contribute most to emissions. Second, more consideration should be given to the governance and institutional quality as the determinant factor in the success of the renewable energy and technological innovation particularly in relation to the South Asian region where institutional capacity varies widely. Third, the hypothesis of Environmental Kuznets Curve can be explored in a more explicit way in the future research to determine whether the South Asian countries are on an edge where their economic growth begins to enhance the environment rather than deteriorate it. Lastly, future modeling with adaptation factors like afforestation, climate finance, and disaster risk reduction being factored in could prove to give a more complex picture of how South Asia can meet mitigation and adaptation targets simultaneously insofar as climate change is concerned.

REFERENCES

Acheampong, A. O., Boateng, E., Amponsah, M., & Dzator, J. (2021). Revisiting the economic growth–energy consumption nexus: Does globalization matter? *Energy Economics*, *102*. https://doi.org/10.1016/j.eneco.2021.105472

Acheampong, A. O., Boateng, E., Amponsah, M., & Dzator, J. (2021). Revisiting the economic growth–energy consumption nexus: Does globalization matter? Energy Economics, 102. https://doi.org/10.1016/j.eneco.2021.105472

Ahmed, K., & Azam, M. (2016). Causal nexus between energy consumption and economic growth for high, middle- and low-income countries using frequency domain analysis. Renewable and Sustainable Energy Reviews, 60, 653–678. https://doi.org/10.1016/j.rser.2015.12.180

Akbar, A., Rehman, A., Ullah, I., Zeeshan, M., & Afridi, F. E. A. (2020). Unraveling the dynamic nexus between trade liberalization, energy consumption, CO2 emissions, and health expenditure in Southeast Asian countries. *Risk Management and Healthcare Policy*, *13*. https://doi.org/10.2147/RMHP.S272801

Ali Gardezi, M., & Samar Abbas, M. (2021). Asymmetric Impact of Interest Rate, Exchange Rate and Oil Prices on Stock Price of BRICS. Journal of Contemporary Macroeconomic Issues, 2(2), 2708–4973.

Alola, A. A., Bekun, F. V., & Sarkodie, S. A. (2019). The dynamics of renewable energy consumption and economic growth: Evidence from emerging economies. Environmental Science and Pollution Research, 26(14), 14594–14602. https://doi.org/10.1007/s11356-019-04882-4

Apergis, N., & Payne, J. E. (2010). Renewable energy consumption and growth in Eurasia. Energy Economics, 32(6), 1392–1397. https://doi.org/10.1016/j.eneco.2010.06.001

Balan, F., Torun, M., & Kilic, C. (2015). Globalization and Income Inequality in G7: A Bootstrap Panel Granger Causality Analysis. *International Journal of Economics and Finance*, *7*(10). https://doi.org/10.5539/ijef.v7n10p192

Bassey, G. E., & Ekong, U. M. (2019). Energy Consumption and Inflation Dynamics in Nigeria: An ARDL Cointegration Approach. *Energy Economics Letters*, *6*(1). https://doi.org/10.18488/journal.82.2019.62.66.83

Beers, P. J., Van Mierlo, B., & Hoes, A. C. (2016). Toward an integrative perspective on social learning in system innovation initiatives. *Ecology and Society*, *21*(1). https://doi.org/10.5751/ES-08148-210133

Behera, S. R., & Dash, D. P. (2017). The effect of urbanization, energy consumption, and foreign direct investment on the carbon dioxide emission in the SSEA (South and Southeast Asian) region. In *Renewable and Sustainable Energy Reviews* (Vol. 70). https://doi.org/10.1016/j.rser.2016.11.201

Ben Jebli, M., & Ben Youssef, S. (2017). Renewable energy consumption and agriculture: Evidence for cointegration and Granger causality for Tunisian economy. International Journal of Sustainable Development & World Ecology, 24(2), 149–158. https://doi.org/10.1080/13504509.2016.1196467

Ben-Salha, O., Dachraoui, H., & Sebri, M. (2021). Natural resource rents and economic growth in the top resource-abundant countries: A PMG estimation. *Resources Policy*, *74*. https://doi.org/10.1016/j.resourpol.2018.07.005

Bilgili, F., Koçak, E., & Bulut, Ü. (2016). The dynamic impact of renewable energy consumption on CO_2 emissions: A revisited Environmental Kuznets Curve approach. Renewable and Sustainable Energy Reviews, 54, 838–845. https://doi.org/10.1016/j.rser.2015.10.080

Butler, J., Wildermuth, G. A., Thiede, B. C., & Brown, D. L. (2020). Population Change and Income Inequality in Rural America. *Population Research and Policy Review*, *39*(5). https://doi.org/10.1007/s11113-020-09606-7

Chen, S., Zhang, H., & Wang, S. (2022). Trade openness, economic growth, and energy intensity in China. *Technological Forecasting and Social Change*, *179*. https://doi.org/10.1016/j.techfore.2022.121608

Chen, Y., Zhou, Y., Raza, S. A., & Sarwar, S. (2024). What we learn from nexus between greener growth and energy-related emissions: Sustainability perspective evidence in context of financial globalization. *Geological Journal*, *59*(2). https://doi.org/10.1002/gj.4883

Coccia, M. (2018). A THEORY OF GENERAL CAUSES OF TERRORISM - HIGH POPULATION GROWTH, INCOME INEQUALITY AND RELATIVE DEPRIVATION. *Archives of Psychology*, *2*(4). https://doi.org/10.31296/aop.v2i4.32

Costantini, V., & Mazzanti, M. (2012). On the green and innovative side of trade competitiveness? The impact of environmental policies and innovation on EU exports. Research Policy, 41(1), 132–153. https://doi.org/10.1016/j.respol.2011.08.004

Cui, N., Nketiah, E., & Ma, X. (2023). Do Green Energy and Information Technology Influence Greenhouse Gas Emitting Countries to Attain Sustainable Development? *Sustainability (Switzerland)*, *15*(18). https://doi.org/10.3390/su151813685

Destek, M. A., & Sinha, A. (2020). Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: Evidence from organisation for economic co-operation and development countries. Journal of Cleaner Production, 242, 118537. https://doi.org/10.1016/j.jclepro.2019.118537

Filippidis, M., Tzouvanas, P., & Chatziantoniou, I. (2021). Energy poverty through the lens of the energy-environmental Kuznets curve hypothesis. *Energy Economics*, *100*. https://doi.org/10.1016/j.eneco.2021.105328

George, G., Merrill, R. K., & Schillebeeckx, S. J. D. (2021). Digital sustainability and entrepreneurship: How digital innovations are helping tackle climate change and sustainable development. Entrepreneurship Theory and Practice, 45(5), 999–1027. https://doi.org/10.1177/1042258719899425

Ghaffar, S., & Ali Gardezi, M. (2024). Financial Inclusion and Energy Poverty Nexus: Evidence from Pakistan. Journal of Asian Development Studies, 13(4), 624–632. https://doi.org/10.62345/jads.2024.13.4.51

Hanif, I., Faraz Raza, S. M., Gago-de-Santos, P., & Abbas, Q. (2019). Fossil fuels, foreign direct investment, and economic growth have triggered CO2 emissions in emerging Asian economies: Some empirical evidence. *Energy*, *171*. https://doi.org/10.1016/j.energy.2019.01.011

Haseeb, M., Kayani, U., Shuaib, M., Hossain, M. E., Kamal, M., & Khan, M. F. (2024). Asymmetric role of green energy, innovation, and technology in mitigating greenhouse gas emissions: evidence from India. *Environmental Science and Pollution Research*, *31*(15). https://doi.org/10.1007/s11356-024-32582-w

Imam, A. (2022). IMPACT OF CARBON TAXES, ECONOMIC GROWTH, GLOBALIZATION, FOREST RENT, INFLATION AND URBANIZATION ON SUSTAINABLE DEVELOPMENT IN

CHINA. *International Journal of Research -GRANTHAALAYAH*, *9*(12). https://doi.org/10.29121/granthaalayah.v9.i12.2021.4450

International Energy Agency (IEA). (2021). India Energy Outlook 2021. IEA. https://www.iea.org/reports/india-energy-outlook-2021

Khan, Z., Ali, S., Umar, M., Kirikkaleli, D., & Jiao, Z. (2020). Consumption-based carbon emissions and international trade in G7 countries: The role of environmental innovation and renewable energy. Science of the Total Environment, 730, 138945. https://doi.org/10.1016/j.scitotenv.2020.138945

Kiran, K., & Gardezi, M. A. (2024). Green Energy Strategies and Their Effect on Natural Resource Sustainability in Pakistan. Bulletin of Business and Economics (BBE), 13(2), 127–135. https://doi.org/10.61506/01.00307

Korankye, B., Wen, Z., Appiah, M., & Antwi, L. (2021). The Nexus Between Financial Development, Economic Growth and Poverty Alleviation: PMG-ARDL Estimation. *ETIKONOMI*, *20*(1). https://doi.org/10.15408/etk.v20i1.15908

Leal, P. A., & Cardoso Marques, A. (2019). Rediscovering the EKC Hypothesis on the High and Low Globalized OECD Countries. In Green Energy and Technology. https://doi.org/10.1007/978-3-030-06001-5_4

Leal, P. H., & Marques, A. C. (2020). Rediscovering the EKC hypothesis for the 20 highest CO2 emitters among OECD countries by level of globalization. *International Economics*, *164*. https://doi.org/10.1016/j.inteco.2020.07.001

Li, X., & Liu, X. (2005). Foreign Direct Investment and economic growth: An increasingly endogenous relationship. *World Development*, *33*(3). https://doi.org/10.1016/j.worlddev.2004.11.001

Li, Z., Shen, T., Yin, Y., & Chen, H. H. (2022). Innovation Input, Climate Change, and Energy-Environment-Growth Nexus: Evidence from OECD and Non-OECD Countries. *Energies*, *15*(23). https://doi.org/10.3390/en15238927

Lund, H. (2007). Renewable energy strategies for sustainable development. Energy, 32(6), 912–919. https://doi.org/10.1016/j.energy.2006.10.017

Magazzino, C. (2018). GDP, energy consumption and financial development in Italy. *International Journal of Energy Sector Management*, *12*(1). https://doi.org/10.1108/IJESM-01-2017-0004

Mondal, M. A. H., Kamp, L. M., & Pachova, N. I. (2018). Drivers, barriers, and strategies for implementation of renewable energy technologies in rural areas in Bangladesh—An innovation system analysis. Energy Policy, 38(8), 4626–4634. https://doi.org/10.1016/j.enpol.2010.04.018

Musah, M., Gyamfi, B. A., Kwakwa, P. A., & Agozie, D. Q. (2023). Realizing the 2050 Paris climate agreement in West Africa: the role of financial inclusion and green investments. *Journal of Environmental Management*, *340*. https://doi.org/10.1016/j.jenvman.2023.117911

Olunuga, A. (2022). FINANCIAL GLOBALIZATION, ECONOMIC GROWTH AND SUSTAINABLE DEVELOPMENT IN EMERGING ECONOMY. *Economic Profile*, *17*(2(24)). https://doi.org/10.52244/ep.2022.24.02

Paramati, S. R., Apergis, N., & Ummalla, M. (2017). The effect of renewable energy consumption on economic growth: Evidence from top renewable energy countries. Energy, 140(1), 68–78. https://doi.org/10.1016/j.energy.2017.08.089

Popp, D. (2002). Induced innovation and energy prices. American Economic Review, 92(1), 160–180. https://doi.org/10.1257/000282802760015658

Porter, M. E., & van der Linde, C. (1995). Toward a new conception of the environment–competitiveness relationship. Journal of Economic Perspectives, 9(4), 97–118. https://doi.org/10.1257/jep.9.4.97

Raihan, A. (2023). The influences of renewable energy, globalization, technological innovations, and forests on emission reduction in Colombia. *Innovation and Green Development*, *2*(4). https://doi.org/10.1016/j.igd.2023.100071

Rasheed, A., Muhammad, D., & Gardezi, A. (2025). JournalofSocialSciencesResearch&Policy(JSSRP) Impact of Financial Development and Innovation on Sustainable Economic Growth:Evidence From Pakistan. In Journal of Social Sciences Research & Policy (JSSRP) (Vol. 48, Issue 2).

REN21. (2021). Renewables 2021: Global Status Report. REN21 Secretariat. https://www.ren21.net/gsr-2021

Sadorsky, P. (2009). Renewable energy consumption and income in emerging economies. Energy Policy, 37(10), 4021–4028. https://doi.org/10.1016/j.enpol.2009.05.003

Saeed, S., & Gardezi, Dr. M. A. (2025). Analyzing The Nexus Between Green Energy, Natural Resources, and Poverty Alleviation In Pakistan. Research Journal for Social Affairs, 3(3), 251–263. https://doi.org/10.71317/rjsa.003.03.0218

Sahoo, M., & Sethi, N. (2023). An Empirical Insight into the Financial Globalization–Growth Nexus via Trade Openness: Evidence from Select South Asian Countries. *Global Business Review*, *24*(2). https://doi.org/10.1177/0972150919893840

Shahbaz, M., Solarin, S. A., Mahmood, H., & Arouri, M. (2013). Does financial development reduce CO_2 emissions in Malaysian economy? A time series analysis. Economic Modelling, 35, 145–152. https://doi.org/10.1016/j.econmod.2013.06.037

Siregar, I., Ma'rifataini, L., Ta'rif, Suprapto, An-Nahidl, N. A., Habibah, N., Sopandi, E., Salman, I., & Munawiroh. (2022). The role of motivation of unified theory acceptance, use of technology model and innovation diffusion theory on e-learning intention of SMEs employee. *International Journal of Data and Network Science*, *6*(4). https://doi.org/10.5267/j.ijdns.2022.8.003

Solarin, S. A., Al-Mulali, U., Musah, I., & Ozturk, I. (2017). Investigating the pollution haven hypothesis in Ghana: An empirical investigation. *Energy*, *124*. https://doi.org/10.1016/j.energy.2017.02.089

Suki, N. M., Sharif, A., Afshan, S., & Suki, N. M. (2020). Revisiting the Environmental Kuznets Curve in Malaysia: The role of globalization in sustainable environment. *Journal of Cleaner Production*, *264*. https://doi.org/10.1016/j.jclepro.2020.121669

Ullah, S., Ozturk, I., Majeed, M. T., & Ahmad, W. (2021). Do technological innovations and financial development improve environmental quality? Evidence from South Asian economies. Environmental Science and Pollution Research, 28(5), 5441–5456. https://doi.org/10.1007/s11356-020-10717-6

UNESCO. (2020). UNESCO Science Report: The race against time for smarter development. UNESCO Publishing.

van Leeuwen, G., & Mohnen, P. (2017). Revisiting the Porter hypothesis: an empirical analysis of Green innovation for the Netherlands. *Economics of Innovation and New Technology*, *26*(1–2). https://doi.org/10.1080/10438599.2016.1202521

Ward, J. W., Michalek, J. J., & Samaras, C. (2021). Air Pollution, Greenhouse Gas, and Traffic Externality Benefits and Costs of Shifting Private Vehicle Travel to Ridesourcing Services. *Environmental Science and Technology*, *55*(19). https://doi.org/10.1021/acs.est.1c01641

Xing, X., Wang, J., Liu, T., Liu, H., & Zhu, Y. (2019). How energy consumption and pollutant emissions affect the disparity of public health in countries with high fossil energy consumption. *International Journal of Environmental Research and Public Health*, *16*(23). https://doi.org/10.3390/ijerph16234678

Yu, H., Peng, F., Yuan, T., Li, D., & Shi, D. (2023). The effect of low-carbon pilot policy on low-carbon technological innovation in China: Reexamining the porter hypothesis using difference-in-difference-in-differences strategy. *Journal of Innovation and Knowledge*, *8*(3). https://doi.org/10.1016/j.jik.2023.100392

Yu, P. (2022). Diffusion of Innovation theory. In *Implementation Science: The Key Concepts*. https://doi.org/10.4324/9781003109945-16

Zhang, C., Shahbaz, M., & Binh, T. N. (2017). Does renewable energy reduce ecological footprint? Evidence from panel data of G20 countries. Renewable and Sustainable Energy Reviews, 67, 708–716. https://doi.org/10.1016/j.rser.2016.09.106

Zhang, L., Leung, M. Y., Boriskina, S., & Tao, X. (2023). Advancing life cycle sustainability of textiles through technological innovations. In *Nature Sustainability* (Vol. 6, Issue 3). https://doi.org/10.1038/s41893-022-01004-5

Zhang, S., & Liu, X. (2024). Nonlinear analysis of tertiary industry on trade globalization-environment nexus in Yellow River Basin in China: evidence from panel smooth transition regression. *Applied Economics*. https://doi.org/10.1080/00036846.2024.2326040

Zhen, H., Gao, W., Yuan, K., Ju, X., & Qiao, Y. (2021). Internalizing externalities through net ecosystem service analysis–A case study of greenhouse vegetable farms in Beijing. *Ecosystem Services*, *50*. https://doi.org/10.1016/j.ecoser.2021.101323.