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Attaining Environmental Sustainability in Pakistan: The Role of Technological Innovation and Renewable Energy

Muhammad Adeel Abbas[1] & Shan-e-Zehra[2]

[1]*Ph.D. Scholar, School of Business and Economics, Universiti Putra Malaysia,*
Email: adeelabbas15690@gmail.com
[2]*Ph.D. Scholar, School of Economics, Bahauddin Zakariya University, Multan, Pakistan,*
Email: Shanezehra717@gmail.com

Abstract

This research examines the impact of renewable energy and technological innovation on environmental sustainability in Pakistan using annual data from 1995 to 2023. The analysis investigates the short and long-run association between CO_2 emissions using the ARDL technique and key explanatory variables, including FDI, industrialization, and human capital. The findings show that renewable energy consumption and technological innovation significantly reduce CO_2 emissions, highlighting their vital roles in promoting environmental sustainability. Conversely, FDI and industrialization are found to increase emissions, indicating their current alignment with pollution-intensive activities. In the short-run, human capital has an insignificant effect on CO_2 emissions. The findings also confirm a stable long-run association among the variables. The study concludes with key policy recommendations to enhance clean energy adoption, support innovation, and regulate environmentally harmful industrial and investment activities.

Keywords: *Environmental Sustainability, Technological Innovation, Renewable Energy, ARDL Model, Pakistan*

Introduction

Environmental sustainability (ES) is essential for preserving the planet's natural resources and maintaining ecological balance. With increasing threats from climate change, pollution, deforestation, and biodiversity loss, sustainable practices are vital for the health of ecosystems and human societies (Cuker et al., 2018). By adopting environmentally sustainable approaches, such as using renewable energy, conserving water, reducing waste, and protecting forests, societies can mitigate environmental damage and promote long-term economic and social well-being. For developed and developing nations, environmental sustainability supports economic growth by encouraging innovation in green technologies and reducing reliance on non-renewable resources. Ultimately, it promotes a more resilient, equitable, and stable world, where development and environmental protection go hand in hand (Nawaz et al., 2022).

Technological innovation (TI) is a vital factor that can influence environmental sustainability. Technological innovation influences the environment through different channels. First, as technology advances, innovation aids nations in achieving industrial process efficiencies (Gozgor, 2017). Second,

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technological advancements result in less consumption of fossil fuels, which benefits the ecology, as well as improved energy-saving products and green energy use (Tang & Tan, 2013). Third, the shift from lower-carbon energy to more sustainable energy is made possible by technological innovation in the energy sector (Jordaan et al., 2017). Fourth, energy efficiency is improved via technical innovation (Dogan, 2016). Fifth, TI may make an ecological production mode possible (Yu & Du, 2019). Thus, the association between TI and CO_2 emissions has been the subject of several recent studies (Mughal et al., 2022; Irandoust, 2016).

Renewable energy (RE) is a strategic commodity for sustainable development (Guo et al., 2022). RE improve energy security, reduce the negative effects of climate change, and ultimately bring reasonable electricity to remote areas, the premise is that numerous RE sources, including solar, wind, refuse and biomass, are both environmentally friendly and cost-effective (Ma et al., 2022). Like most concepts, renewable energy lacks a general definition; nonetheless, here are similar themes when elucidating it (Joseph, 2019). These contain the requirement that any energy sources be ecologically beneficial, long-lasting, and capable of replenishing themselves when utilized to be considered renewable. According to Chel & Kaushik (2018), renewable energy is any energy produced eco-friendly manner that allows the earth to lower carbon emissions while still providing for humankind's essential energy needs. Similar arguments were made by Oladeji (2014), who claimed that because renewable energy is produced in an eco-friendly way, less CO_2 is accumulated in the atmosphere.

The most significant global energy source is non-renewable energy sources, probable carriers of energy that have been created but cannot be replenished. Environmental damage and climate disruption are the main consequences of using non-RE sources (Zarkovic et al., 2022). Motesharrei et al., (2014) state that excessive consumption, unfair wealth distribution, and unchecked exploitation of non-renewable natural resources could cause industrial society to collapse over several decades. The current standard of living is at risk due to the depletion of non-RE sources like coal, gas and oil so consequently augment in energy consumption which is an effect of the increasing global population.

Pakistan faces mounting environmental challenges, including air and water pollution, deforestation, rising carbon emissions, and increasing vulnerability to climate change. These problems threaten the population's health, economic growth and ecological balance (Ahmed et al., 2015). Despite the increased awareness, the nation fails to adopt effective measures towards environmental sustainability. One crucial gap is that technological innovation, renewable energy solutions have not been integrated into the national environmental practice and policy to the desired level. Technological innovation can increase energy efficiency, minimize emissions, and promote sustainable industrial and agricultural processes. But the innovation capacity of Pakistan is not developed because of poor investment in innovation, lack of research infrastructure and poor policies. The implementation of RE, containing solar, wind and hydro power, has been slow with financial, regulatory and institutional barriers to implementation at the same time. Unless there is a definitive plan for how to use technology and increase the REC, the environmental degradation in Pakistan is more than likely to increase faster, undermining its commitments to the Paris Agreement and SDGs. Hence, the purpose of this analysis is to examine the influence of green energy and TI on the environmental sustainability (ES) of Pakistan. It seeks to determine major drivers, challenges, and policy frameworks to efficiently use these tools for a greener and more resilient future.

Literature Review

Numerous researchers investigated technological innovation (TI) and renewable energy (RE) concerning environmental sustainability such as Obobisa et al., (2022) studied the long-term associations between economic growth (EG), RE, fossil fuel energy, institutional quality, and green technical innovation and the environmental degradation (ED) in 25 African economies during 2000 to 2018 time period. The results revealed that both green technical advancement and RE have a considerable adverse influence on ED. Subsequently, fossil fuel energy usage, institutional quality and economic expansion contribute to an argument in ED. Mughal et al., (2022) examined the causal nexus existing amid energy consumption (EC), environmental pollution (EP), technological innovation (TI), and sustainable economic growth (SEG) using a sample of South Asian countries from 1990 to 2019. The findings demonstrate that environmental quality in South Asia has significantly worsened. Bangladesh had exhibited a positive and substantial influence on ED in relation to the NRE, RE and TI. However, the EKC hypothesis holds with the negative and positive growth and GDP squared values, respectively. Adebayo (2022) evaluated the outcome of RE on CO_2 emissions in Canada between 1990 and 2018, considering global trade and economic growth. A novel dynamic ARDL approach was used in this study. The application of RE, global trade, political risk and increases economic growth mitigated environmental degradation. Additionally, the causality results showed that CO_2 emissions in Canada may be predicted over the long run by economic growth (EG), political risk, the usage of renewable energy, and global trade. Dagar et al., (2022) explored the influence of financial development (FD), natural resources, industrialization, REC and total reserve on ED in 38 OECD nations and employed the dynamic panel data models and panel data from 1995 to 2019. The results of their research indicate that industrialization, FD and total reserves contribute to environmental degradation, REC and natural resources reduces the ED in OECD economies.

Kartal et al., (2022) examined the impacts of EC on ED in the US using periodic data from January 1989 and September 2021. The results indicated that the EC has a wide influence on the ED. On behalf of outcomes, the policymakers in the United States ought to focus on cutting fossil fuels and expanding RE sources through the conversion of the energy systems to curb the emission of CO_2, considering the dynamic consequences of energy consumption with time. Khan et al., (2020) considered environmental sustainability in SAARC countries between 2005 and 2017. The outcomes showed that green practices at the national level, such as RE, eco-friendly laws, regulatory pressure, and the ecological usage of natural resources, were highly and favorably correlated with environmental sustainability. Amri & Amri (2019) investigated the connection between environmental sustainability and innovation in Tunisia between 1971 and 2014. The study showed that energy use had a direct influence on CO_2 emissions. While there was no pivotal association between technical advances and economic development or CO_2 emissions, there was a one-way impact in the short term and long term from the technological innovation variable to the energy consumption one. Omri et al., (2019) investigated the factors that influence ES in Saudi Arabia. The outcomes indicate that environmental degradation favors financial growth, foreign commerce, FDI and per capita income. The Saudi Arabian case validated the EKC hypothesis; environmental deterioration was highly responsive to FDI, foreign trade and financial development level, thus thresholds were subsequently established.

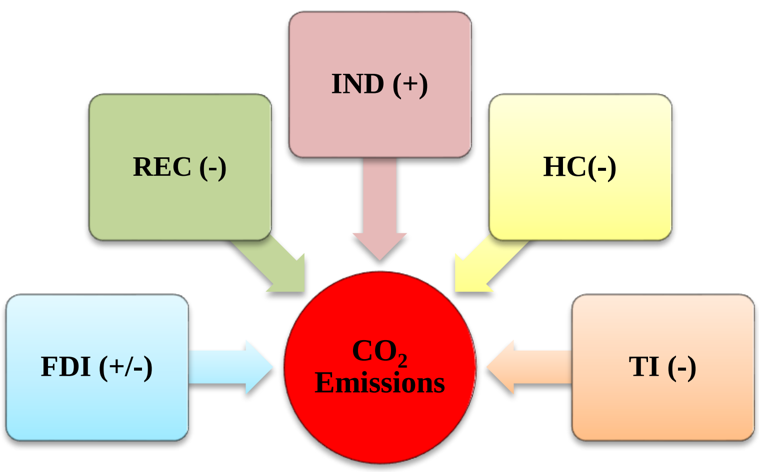
Data and Methodology

To examine the association among TI, renewable energy and environmental sustainability, this analysis used Pakistan's annual time series dataset from 1995 to 2023. The technological innovation is measured by using research and development expenditures as a percentage of GDP, renewable energy is measured by using REC (as a percent of total energy consumption), and environmental sustainability is measured by CO_2 emissions. The data is collected from World Development Indicators. The study built the following econometric model to analyze the effect of TI and RE on ES in Pakistan.

$$ENV_i = \beta_o + \beta_1 FDI_i + \beta_2 TI_i + \beta_3 REC_i + \beta_4 HC_i + \beta_5 IND_i + u_i \qquad (1)$$

Where ENV indicates environmental sustainability (CO_2 emissions), FDI indicates foreign direct investment (Percentage of GDP), TI refers to the technological innovation (R&D expenditures as a percentage of GDP), REC indicates renewable energy (Percentage of total energy consumption), HC is human capital (secondary school enrolment), IND indicates industrialization (Percentage of GDP) and u_i is the error term.

Figure 1: Conceptual Model



For data estimation, many econometric procedures are applied. First, the Augmented Dickey-Fuller (ADF) test is a statistical method used to check the stationarity of time series data, ensuring that variables do not exhibit unit roots, which could lead to spurious regression results. It tests whether a variable's current value is significantly related to its past values. Second, the ARDL Bound Test of cointegration, developed by Pesaran et al., (2001), determines a long-run relationship among variables in a model. It is beneficial when variables are integrated at mixed levels (I(0) and I(1)) but not at I(2). The F-statistic is compared against critical value bounds. Cointegration exists if it exceeds the upper bound; if it falls below the lower bound, no cointegration is found. Lastly, the Autoregressive Distributed Lag (ARDL) model is then employed to estimate both short-run and long-run associations among variables, especially when variables are integrated at different levels (I(0) or I(1)). ARDL is suitable for small sample sizes and provides robust long-term coefficient estimates even when the underlying variables are not uniformly stationary.

Data Analysis

Descriptive Analysis

The 2 shows the outcomes of descriptive statistics. The results show that the mean values of ENV, FDI, TI, REC, HC and IND are 0.727, 0.874, 0.034, 48.065, 33.854 and 19.827, respectively. Similarly, the maximum values of ENV, FDI, TI, REC, HC and IND are 0.918, 3.112, 0.505, 59.091, 39.443 and 22.103, correspondingly. The minimum values of ENV, FDI, TI, REC, HC and IND are 0.620, 0.210, 0.026, 41.055, 26.269 and 17.159, respectively. Except IND all other variables have a positively skewed distribution.

Table 2: Descriptive Statistics

Variables	Mean	Maximum	Minimum	SD	Skewness	Kurtosis
ENV	0.727	0.918	0.620	0.081	0.417	2.471
FDI	0.874	3.112	0.210	0.522	1.543	4.033
TI	0.034	0.505	0.026	0.652	0.709	1.096
REC	48.065	59.091	41.055	4.444	0.291	2.331
HC	33.854	39.443	26.269	3.660	0.055	1.783
IND	19.827	22.103	17.159	1.595	-0.205	1.835

Correlation Analysis

Table 3 shows that ENV (CO_2 emissions) is positively correlated to the FDI and industrialization, while ENV is negatively correlated with the TI, REC and HC.

Table 3: Correlation Matrix

Correlation	ENV	FDI	TI	REC	HC	IND
ENV	1.000					
FDI	0.116	1.000	0.103			
TI	-0.597	0.103	1.000			
REC	-0.473	0.575	0.335	1.000		
HC	-0.769	0.250	0.554	0.281	1.000	
IND	0.190	0.266	0.373	0.118	-0.150	1.000

Unit Root Analysis

The ADF test is applied to inspect the stationarity level of the variables. The results in Table 4 show that FDI, TI, REC and IND are all integrated at order one I(1), whereas ENV and HC are integrated at order zero I(0). The findings demonstrate that the order of integration is mixed, which proposes that the ARDL model is good for estimating long-term parameters.

Table 4: ADF Test Estimates

Variables	Level		1st Difference		Outcomes
	t-stat.	Prob.	t-stat.	Prob.	
ENV	-3.033	0.012	--	--	I(0)
FDI	--	--	-4.332	0.004	I(1)
TI	--	--	-2.706	0.013	I(1)
REC	--	--	-5.223	0.000	I(1)
HC	-5.605	0.001	--	--	I(0)
IND	--	--	-4.842	0.001	I(1)

Bound Test Analysis

The study employed the ARDL bound test for the long-run cointegration of variables. The results indicate that the F-statistic value is greater than the upper bound values at the 1 percent significance level, indicating that the variables ENV, TI, FDI, REC, HC and IND are cointegrated in the long-run.

Table 5: Bound Test Analysis

Null Hypothesis: No Long-Run Association				
Test	**Value**	**Significance**	**I(0)**	**I(1)**
F-Statistic	4.8510	10%	2.08	3
K	5	5%	2.39	3.38
		2.5%	2.7	3.73
		1%	3.06	4.15

ARDL Long-Run Analysis

Long-run estimates of the ARDL model are presented in this section. The outcomes show that FDI has a positive coefficient (0.0524) and a p-value of 0.0726, indicating a positive but weakly significant link with CO_2 emissions. This advocates increased FDI may contribute to environmental degradation, likely due to investment in emission-intensive sectors such as manufacturing or energy (Iram et al., 2024). In contrast, technological innovation is negatively and significantly linked to environmental degradation, suggesting that technological advancements contribute to environmental sustainability by reducing emissions. The negative sign confirms that innovation may improve production efficiency or foster cleaner technologies, lowering carbon footprints (Obobisa et al., 2022; Yu et al., 2019). RE usage also significantly negatively affects emissions (coefficient = -0.0422, p = 0.0170). This confirms the role of RE in mitigating ED. The switching from fossil fuels to cleaner energy sources such as solar or wind probably lowers CO_2 emissions. Industrialization is imperative for better macroeconomic performance, but it can adversely influence the country's environment (Dogan, 2016; Irandoust, 2016; Iram et al., 2024). The outcomes also suggest that IND is positively and strongly associated to the emission of carbon dioxide in Pakistan. These results suggest that industrialization increases CO_2 emissions due to increased energy consumption (Dagar et al., 2022; Opoku & Aluko, 2021).

Table 6: ARDL Long-Run Analysis

Dependent Variable: Environment (CO_2 Emissions)				
Variable	**Coefficient**	**SE**	**t-statistic**	**Prob.**
FDI	0.0524	0.0268	1.9536	0.0726
TI	-0.0505	0.0201	-2.5127	0.0260
REC	-0.0422	0.0163	-2.5881	0.0170
HC	-0.0045	0.0075	-0.6076	0.5539
IND	0.0297	0.0130	2.2827	0.0399
C	1.8834	1.0957	1.7189	0.1093

ARDL Short-Run Estimates

According to the ECM term (-0.4574) which is negative and statistically significant (p=0.0001), deviations from the long-run equilibrium are corrected at a rate of 45.74% each year. This specifies that the correction rate is increasing significantly. This proves the stability of the model as well as the incidence of a significant link between the variables over the long term.

Table 7: ARDL Short-Run Analysis

Dependent Variable: Environment (CO_2 Emissions)				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
D(ENV(-1))	0.3186	0.1256	2.5368	0.0248
D(TI)	0.0038	0.0051	0.7495	0.4668
D(RE)	0.0157	0.0050	3.1039	0.0084
D(HC)	-0.0233	0.0058	-4.0029	0.0015
D(HC(-1))	-0.0131	0.0055	-2.3953	0.0324
ECM(-1)	-0.4574	0.0805	-5.6778	0.0001

Model Diagnostic Analysis

The diagnostic tests confirm the robustness of the ARDL model. The Breusch-Godfrey (BG) test reveals an absence of autocorrelation (p=0.1554) and Breusch-Pagan-Godfrey (BPG) test indicates no presence of heteroskedasticity (p=0.1138). The model specification is checked by Ramsay RESET (RR) test where (p=0.1650), while the Jarque-Bera (JB) test implies that the residuals follow a normal distribution (p=0.4718). These results validate the model's reliability and appropriateness for analyzing the association between the selected variables and CO_2 emissions.

Table 8: Model Diagnostic Analysis

Issue	**Test**	**Statistic**	**Prob.**	**Outcomes**
Autocorrelation	BG	2.2982	0.1554	Not Exist
Heteroskedasticity	BPG	1.7249	0.1138	Not Exist
Model Specification	RR	2.2377	0.1650	Correct
Residual Normality	JB	1.5021	0.4718	Normal

Conclusions

This study analyzed the role of TI and RE in impacting the ES in Pakistan. The study found that technological innovation and REC significantly reduce CO_2 emissions in short and long run. This confirms that cleaner technologies, improved energy efficiency and a switch to green source of energy sources effectively address environmental challenges. On the contrary, foreign direct investment and industrialization were determined to exert a statistically beneficial impact on CO_2 emissions. These outcomes propose that FDI can contribute to economic growth; its current orientation in Pakistan is likely directed towards pollution-intensive industries. Similarly, industrialization contributes to increased emissions due to substantial dependence on fossil fuels and a lack of environmental safeguards. Human capital was found to have an insignificant effect on environmental outcomes, implying that education and workforce development improvements have not yet translated into environmental benefits. This may be due to a lack of environmental focus in the education system or limited green skill development. The error correction term of short-run was significant and inverse, suggesting a steady adjustment toward long-run equilibrium. The diagnostic tests confirmed that the model is free from autocorrelation, heteroskedasticity, misspecification and the residuals are normally distributed, reinforcing the robustness of the model. The study concludes that RE and TI are key drivers of environmental sustainability in Pakistan, while FDI and industrialization pose environmental challenges. Therefore, there is a strong need for industrial policy and FDI management reforms, along with greater investments in clean energy and innovation to ensure a sustainable and resilient environmental future.

Policy Implications

The study results also have significant policy implications for the environmental policy in Pakistan. To begin with, the significant negative association between TI and CO_2 emissions is quite strong, indicating the necessity to invest more in research and development, particularly in green technologies. The policymakers should grant tax relief and subsidies to encourage the use of RE, energy efficiency, and low-carbon technologies. Second, the transition from fossil fuels to clean energy sources like solar, wind and hydropower must be accelerated due to the usefulness of such RE in sinking ED. The policies must strengthen the clean energy infrastructure, eliminate regulations, and encourage the development of public-private partnerships to increase the adoption. Third, FDI and industrialization play a role in ED today; thus, tougher environmental regulations are needed on foreign and domestic investors. The government should embrace green FDI screening procedures and ensure environmental standards are observed in industrial areas. Finally, in the short-term human capital did not prove to be significant, but the incorporation of environmental education and green skills training in the curriculum can be of benefit in the long-term. Overall, a coherent policy system fostering innovation, stimulating clean energy, controlling dirty industries, and developing green human resources is the key to sustainable development in Pakistan.

Limitations of the Study

Although the study is very insightful, there are limitations involved. First, the analysis is done at the national level of Pakistan, which does not represent the regional environmental differences or local effects of industrialization and innovation. Second, the study employs CO_2 as the only measure of environmental sustainability, which may fail to capture other important aspects of environmental sustainability, like biodiversity, water quality, and land degradation. Third, despite the ARDL model's ability to capture short and long-term relationships, it might not capture structural breaks or external shocks, including significant policy reforms or international climate agreements, which affect the emissions. Fourth, technological innovation measures based on R&D spending might not completely indicate the quality or performance of the innovation outcome. Finally, data was limited, which did not allow including many other variables that are also important, including institutional quality, environmental regulations, or green finance, which would have added to the analysis. These gaps should be filled in the future to get a more in-depth understanding.

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