Remittances Review
January, 2024
Volume: 9, No: 1, pp. 631-653
ISSN: 2059-6588 (Print) | ISSN: 2059-6596 (Online)

Received: 16 November 2023, Accepted: 22 December 2023

DOI: https://doi.org/10.33182/rr.vx9il.58

EXAMINING THE ENVIRONMENTAL IMPLICATIONS OF FINANCIAL DEVELOPMENT, FDI, AND TECHNOLOGICAL INNOVATION: INSIGHTS FROM PAKISTAN

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Abstract

One of the key solutions to achieving "sustainable development" in Pakistan is to narrow the divide between economic activities and environmental quality. This study investigates the dynamic influence of GDP, financial development, foreign direct investment, population density, renewable energy consumption, and technological innovation on environmental degradation in Pakistan from 1990 to 2020. ADF and Phillips Perron unit root tests confirmed the stationarity of variables with a mix of level and first difference. Moreover, the F-bounds test revealed the presence of cointegration in the model. By using the ARDL approach, the long-term estimates highlight the significant contribution of the aforementioned variables in shaping environmental outcomes. Key insights include the negative impact of GDP per capita and financial development on environmental degradation, emphasizing the importance of sustainable economic policies and efficient resource allocation. Additionally, technological innovation positively influences environmental degradation, underscoring the need for green innovation and clean technology adoption. The study also reveals the positive linkage between population density and environmental degradation, emphasizing the importance of sustainable urban planning. Lastly, renewable energy consumption negatively affects environmental degradation, underscoring the significance of transitioning to renewable energy sources. The error correction model showed the presence of convergence, which confirmed short-run equilibrium. Granger causality showed mixed unidirectional and bidirectional linkages of carbon emissions with each independent variable. Based on these findings, policy recommendations include promoting sustainable economic development, strengthening the financial sector's focus on eco-friendly investments, fostering green innovation, implementing sustainable urban planning strategies, and encouraging renewable energy adoption.

Keywords: Carbon Emission, Foreign direct investment, Financial Development, Renewable Energy Consumption, ARDL Method.

1. Introduction

The primary focus of global economies is to achieve the Sustainable Development Goals (SDGs), which have been a continuous priority for developing and emerging nations as they strive for rapid economic progress. Emerging nations are actively embracing liberalization and globalization to gain a competitive advantage in the global economy. They are actively seeking foreign direct investment (FDI) to support their economic growth (Wako, 2021). Developed countries find emerging and developing nations appealing due to their abundant and cost-effective raw materials as well as low-cost labor. Developing nations attract highly polluting industries from advanced economies due to the absence of strict environmental regulations. Companies relocate to developing nations to evade stringent standards, driven by a desire to evade stringent standards (Wang & Zhang, 2020). Consequently, host economies experience an influx of capital through FDI. Research conducted over the past few decades has shown that FDI has a substantial impact on employment opportunities, knowledge transfer, and improved managerial skills, ultimately leading to an enhanced standard of living for a significant portion of the population in the region (Malik et al., 2023; Pradhan et al., 2022). However, the expansion of economic activities in FDI-hosting economies relies heavily on energy consumption and fuel combustion. This growth also entails the conversion of agricultural and forest lands into new industrial sites, resulting in ecological imbalances. In the context of sustainable development, there has been growing concern about the relationship between gross domestic product (GDP) and environmental degradation (Mohsin et al., 2023; Alharthi et al., 2022; Ahmad & Wu, 2022). Traditional economic growth models have long regarded GDP as a vital measure of economic progress and societal well-being, often neglecting the environmental consequences of such growth. Consumption and production patterns driving the relentless pursuit of GDP expansion have resulted in unprecedented levels of environmental degradation, including climate change, deforestation, pollution, and loss of biodiversity (Wassie, 2020; Thornton & Herrero, 2010).

Consequently, these industrial units become significant sources of carbon emissions, contributing to poor environmental quality (Huang et al., 2023; Yu-Ke et al., 2022; Zhang et al., 2022). In recent years, there has been a growing body of literature that delves into the environmental and economic implications of technological innovations. Scholars have acknowledged the substantial impact of these innovations in enhancing productivity and stimulating economic growth (Chen et al., 2023; Mohamed et al., 2022; Acheampong et al., 2022). One key area where technology has shown promise is in mitigating environmental degradation. By embracing technological advancements, we can achieve greater resource efficiency, harness renewable energy sources, implement effective pollution control measures, manage waste more efficiently, and enhance environmental monitoring (Ramzan et al., 2023; Malik et al., 2023; Saqib et al., 2023; Kunkel & Matthess, 2020). Resource efficiency lies at the heart of sustainable development. Technological innovations allow us to optimize the use of resources, reducing waste and maximizing their productivity. Furthermore, the consumption of renewable energy sources not only aids in diversifying the energy mix but also plays a crucial role in dropping greenhouse gas emissions and addressing the influences of climate change (Sovacool et al., 2021; Elum & Momodu, 2017).

Additionally, the implementation of pollution control measures is vital for the preservation of our environment. Through technological innovations, we can develop and deploy advanced systems to monitor and control pollution levels, thereby minimizing the negative impacts on ecosystems, human health, and overall environmental quality (Liu et al., 2022). Effective waste management is another critical aspect where technology can make a significant difference (Prajapati et al., 2021). Implementing advanced waste management practices reduces the amount of waste sent to landfills, promotes recycling and circular economy initiatives, and minimizes the environmental footprint associated with waste disposal (Maiurova et al., 2022; Romero, Hernández, & Romero, 2018). Furthermore, embracing sustainable technologies not only helps address immediate environmental challenges but also contributes to building a more sustainable future (Silvestre & Ţîrcă, 2019). By adopting and supporting these innovations, we can create a conducive environment for economic growth while safeguarding our planet's resources and ecosystems.

In addition to economic factors, researchers have also directed their attention towards demographic aspects and have discovered a substantial connection with environmental quality. Scholarly works shed light on this relationship, highlighting the direct association between human activities and escalating carbon emissions (Li & Ullah, 2022; Sarkodie et al., 2020). Demographic factors primarily encompass population structure and population size. One specific demographic factor, the density of the population, has gained increasing recognition in recent literature as a critical element linked to carbon emissions. Studies conducted by Saleem et al. (2018), Ozcan and Ulucak (2021), and Yue et al. (2020) support this acknowledgment. Taking the case of Pakistan as an example, the population density, measured in terms of the number of people per square kilometer of land, has witnessed an increase from 88 in 1975 to 290 in 2021 (World Bank, 2022). In 2021, Pakistan documented per capita carbon emissions of 1.04 metric tons. This metric provides an indication of the average amount of carbon emissions produced by each individual in the country.

Moreover, a number of researchers have put forth the argument that the correlation between financial development and pollution implies that advancements in the financial sector can contribute a crucial part in increasing environmental conditions by reducing emissions (Islam, 2022; Zakaria & Bibi, 2019). Conversely, Dogan and Turkekul (2016) have argued that there is no significant association between financial development and environmental degradation. Contrarily, several studies have revealed negative environmental impacts associated with economic advancement (Wang et al., 2022; Assi et al., 2021). This conflicting relationship necessitates a thorough examination in order to formulate effective financial policies aimed at improving environmental quality in Pakistan.

The primary contribution of this study lies in the development of a comprehensive framework to examine the intricate relationship between foreign direct investment, GDP, population density, financial development, technological innovations, and carbon emissions in Pakistan. By analyzing these key variables using the ARDL approach, the study aims to offer valuable insights into the long-run and short-run dynamics that influence environmental sustainability amidst economic

January, 2024
Volume: 9, No: 1, 2024
ISSN: 2059-6588 (Print) | ISSN: 2059-6596 (Online)

growth and technological advancements. The findings from this research endeavor have the potential to inform policymakers, investors, and stakeholders on the most effective strategies to promote sustainable development and bridge the gap between economic activities and environmental quality in Pakistan. Through this holistic approach, the study contributes to the ongoing global efforts towards achieving a more sustainable future for the nation and beyond.

2. Theoretical Framework

The Environmental Kuznets Curve (EKC) provides a theoretical framework for examining the correlation between a country's gross domestic product (GDP) and its impact on the environment (Bilgili et al., 2023; Guo et al., 2022; Boubellouta & Kusch-Brandt, 2020; Nikensari et al., 2019). According to the EKC, as a nation's GDP per capita rises, environmental degradation initially increases but eventually decreases, forming an inverted U-shaped curve. During the early stages of economic development, industries prioritize production and profitability, often leading to higher pollution levels and resource depletion.

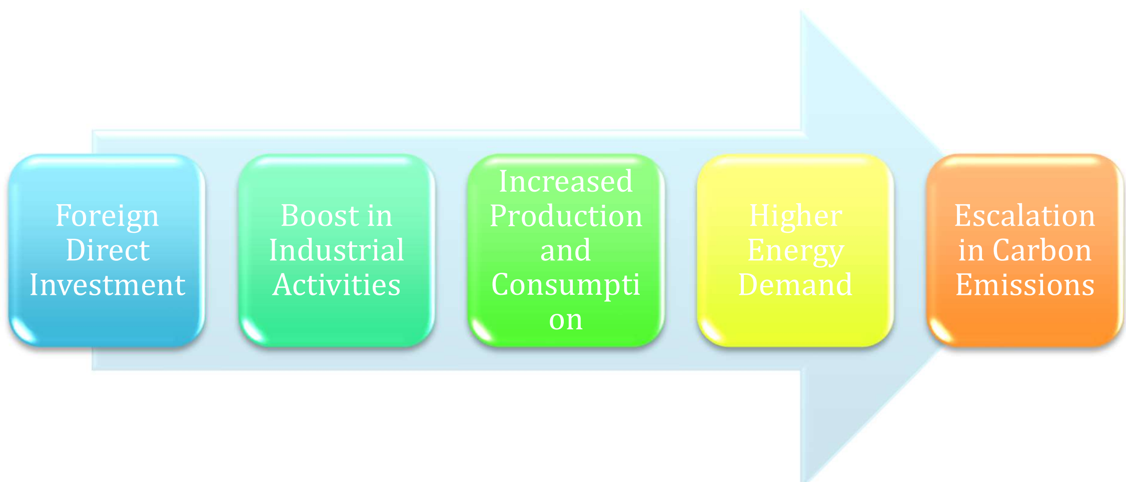
However, as countries reach a certain income threshold, various factors come into play, leading to a reduction in environmental degradation. Technological advancements play a crucial role by facilitating the adoption of cleaner technologies and more efficient resource management practices. Additionally, as environmental awareness and education grow among the population, there is an increased demand for sustainable practices. Governments respond by implementing stricter environmental regulations that compel industries to mitigate their environmental impact. Moreover, economic restructuring occurs, shifting away from pollution-intensive industries towards cleaner sectors such as services and knowledge-based industries, further contributing to environmental improvement. Figure 1 shows how GDP improves environmental quality by reducing carbon emissions.

Figure 1. Theoretical Linkage between GDP and Carbon Emissions

Although the EKC offers valuable insights into the potential relationship between GDP and environmental degradation, it's important to acknowledge that the shape of the curve and the income threshold can vary among countries (Uche et al., 2023; Jahanger et al., 2023). Moreover, certain environmental challenges, like climate change, may not conform to the simple EKC pattern and require more comprehensive solutions.

Furthermore, literature has evidenced for significant linkage between FDI and carbon emission through analyzing the Pollution Heaven and Pollution Halo Hypothesis (Ahmad et al., 2021; Yilanci, et al., 2023; Mert & Caglar, 2020;; Balsalobre-Lorente et al., 2019). The Pollution Heaven hypothesis suggests that FDI flows from advancedeconomies to developing economies with weaker environmental regulations, potentially leading to increased pollution and environmental degradation (Apergis et al., 2023; Sapkota & Bastola 2017). Multinational corporations (MNCs) from developed nations may relocate their production facilities to countries with lax environmental standards to minimize compliance costs and maximize profits, thus contributing to negative environmental consequences. Figure 2 represents the adverse association between FDI and carbon emissions.

Figure 2. FDI and Carbon Emission Linkage



In contrast, the Pollution Halo hypothesis proposes that FDI can have a positive effect on the environment. It argues that FDI brings advanced technologies, managerial practices, and capital investment that promote cleaner and more sustainable production processes (Zhou et al., 2022; Abdo et al., 2023). MNCs from developed countries can transfer their advanced environmental technologies and practices to their subsidiaries in developing countries, leading to improvements in environmental quality. However, the actual relationship between FDI and environmental degradation is complex and depends on factors such as industry characteristics, host country environmental policies, and corporate social responsibility practices. Consequently, a nuanced analysis is necessary to understand the environmental impacts of FDI and implement appropriate policies for sustainable development. Moreover, technology innovation is closely intertwined with environmental quality as it drives the development of cleaner technologies, enhances resource efficiency, enables the advancement of renewable energy solutions, and strengthens environmental monitoring and management practices (Ramzan et al., 2022). These technological advancements empower us to reduce pollution, optimize resource utilization, shift towards sustainable energy sources, and effectively safeguard and regulate our environmental resources, leading to a healthier and more sustainable planet for future generations.

3. Literature Review

The literature review section aims to explore the existing body of research on the influence of various factors on carbon emissions. This study focuses on assessing the influence of five key variables, namely GDP, financial development, foreign direct investment (FDI), technological innovations, and population density. Understanding the linkage between these factors and carbon emissions is crucial in formulating effective policies and strategies to address environmental concerns. By reviewing relevant studies and analyzing their findings, this section aims to provide valuable insights into the complex interplay between these variables and their implications for carbon emissions. Recently, numerous studies have attempted to sort out significant factors of environmental quality by using carbon emissions, ecological footprints, and greenhouse gases as proxyes of environmental degradation (e.g., Shaheen et al., 2022; Acevedo-Ramos et al., 2023; Ponce et al., 2023; Uddin et al., 2023; Hussain & Rehman, 2021). Wang et al. (2023) examined globalization, FDI inflow, GDP growth, innovation, financial development, and urbanization's impact on carbon emissions in China. Findings show the negative effects of globalization, FDI, and innovation, while GDP growth, financial development, and urbanization enhance environmental degradation. Rehman (2020) examined the impact of GDP growth, population density, and international trade on environmental quality and energy consumption in India for the period 1971–2011 using the ARDL method. The findings indicated a positive influence of population density and GDP growth on energy consumption. Additionally, a direct linkage was observed between energy consumption, population density, and environmental pollution in India. Wang et al. (2020) examine carbon emissions dynamics in N-11 countries for the time period 1990–2017 and introduce innovative factors. Empirical estimations show positive links between carbon emissions, financial development, and GDP, while technological innovation and renewable energy have adverse relationships. Hao et al. (2020) examined technological innovations and FDI's impact on environmental degradation in 30 selected Chinese provinces for a time span of 1998–2016. Panel regression analysis revealed FDI's positive environmental role. Technological innovation significantly reduced smoke dust and sulfur dioxide but had an adverse effect on chemical oxygen demand. Tan et al. (2021) employed ARDL to analyze the effects of energy consumption, FDI, financial development, and domestic credit on air quality in China during the period of 1995–2018. Findings revealed a long-term positive impact of energy consumption on air quality and a short-term positive impact of financial development and domestic credit. The study recommended promoting low-interest domestic credit for renewable energy adoption and improved air quality.

In their investigation spanning from 1990 to 2018, Zafar et al. (2020) explored the impact of urbanization, FDI, education, and energy consumption on environmental pollution in Asia. Employing FMOLS and DOLS, they revealed that FDI, urbanization, and education significantly influenced environmental quality, while energy consumption and income were detrimental. They proposed policies encouraging green technology, boosting educational budgets, and implementing planned urbanization for a sustainable environment. Abbas et al. (2021) examined the influence of energy consumption, regulatory quality sustainability, and FDI on greenhouse gas emissions in 27 Asian economies for the time span of 2001–2018. The GMM analysis revealed the significant role of regulatory quality in reducing GHG emissions. Energy consumption had an adverse effect on

GHGs, while FDI supported the development of institutional quality. Ochoa-Moreno et al. (2021) employed DOLS to investigate the effects of FDI on environmental quality across various income groups (low, middle, and high) during 1990–2018. Their findings indicated an inverse association between FDI and carbon emissions. Their empirical results led to the recommendation of using short-term FDI to stimulate economic growth, while long-term FDI should be accompanied by stringent environmental regulations. Adams et al. (2020) emphasized the impact of urbanization and transportation on environmental degradation in 19 economies in sub-Saharan Africa (SSA) from 1980 to 2011. Utilizing the GMM approach, the study found a direct linkage between transport energy consumption and environmental pollution. Furthermore, urbanization exhibited a negative coefficient value for carbon emissions. Yahaya et al. (2020) used the ARDL approach to analyze Nigeria's population-environment nexus (1980–2014). Long-run findings revealed a positive influence of financial development and population growth on CO2 emissions, while trade improved environmental quality. The study highlighted the importance of public awareness and population regulation to enhance environmental quality. Furthermore, Huang et al. (2023) applied the ARDL method to investigate the connection between business cycle synchronization, urbanization, FDI, exports, imports, and environmental degradation in Pakistan for the time period 1975–2017. The study revealed that all explanatory factors, except FDI, were significant contributors to environmental degradation. Specifically, imports and urbanization exhibited a direct and significant influence on environmental degradation.

Cheng et al. (2020) studied pollution heaven and halo hypotheses in 285 Chinese cities for a time span of 2003–2016. FDI positively influenced urban environmental pollution, but its intensity varied with cities' economic development. Early industrialization had less environmental harm than later stages. Using a dynamic spatial method, Wang et al. (2021) investigated the nexus between FDI and CO2 emissions in 30 selected provinces of China from 2004 to 2016. The study revealed a non-linear, "inverted U-shaped" connection between FDI and CO2 emissions. The initial influence of FDI on CO2 emissions raised concerns for policymakers regarding environmental quality. Furthermore, the study concluded that the emission trading system has a negative effect on carbon emissions. Moreover, Gyamfi et al. (2022) examined the effects of technological innovation, industrialization, FDI inflows, total reserves, and natural resources on carbon emissions in BRICS economies during 1990–2019. Using AMG, Driscoll-Kraay estimators, and CCEMG, the study assessed the relationship among environmental quality factors. Findings showed renewable energy and technological innovations reduced carbon emissions, while FDI and industrialization harmed the environment. Chen and Lee (2020) examined the effect of technological innovation and R&D intensity on CO2 emissions across 96 global economies for the time span of 1996–2018. Using a spatial econometric method, the study revealed that technological innovations did not have a significant mitigation effect on CO2 emissions. Furthermore, R&D intensity was found to have a direct effect on carbon emissions in certain nations. Sinha et al. (2020) employed the rolling window heterogeneous panel casualty approach and bootstrapped quantile regression to assess the influence of technological innovations on environmental quality in the Next 11 (N11) economies for the time duration of 1990–2017. The study revealed a negative impact of technology on air pollution in low and medium quantiles, while a positive influence was observed in higher quintiles.

Xie et al. (2020) employed panel smooth transition regression to analyze FDI's spillover impact on carbon emissions in emerging economies. Results indicated a positive impact of FDI on carbon emissions, yet FDI's influence through GDP growth could mitigate environmental degradation. Nonlinear marginal analysis revealed significant V+W-shaped effects of FDI on environmental degradation, exhibiting regional heterogeneity. For instance, Islam et al. (2021) employed dynamic ARDL simulations to examine the effects of technological innovations, economic growth, FDI, and globalization on environmental quality in the context of Bangladesh from 1972 to 2016. The study revealed that energy consumption, trade, urbanization, and economic growth had a negative impact on environmental quality. Conversely, technological innovations, FDI, and globalization played a supportive role in enhancing environmental quality in Bangladesh.

4. Data and Methodology

Taking into consideration the preceding conversation, this study presents a framework that aims to examine the influence of foreign direct investment, GDP, population density, financial development, and technological innovations on carbon emissions in Pakistan. To analyze the environmental degradation, the model used in this research adopts the subsequent functional form, represented by Equation 1:

$$COEM = f\ (GDPPC, TINO, FDINV, PDEN, FDEV, RECON) \quad (1)$$

The variables are described in the following table (1), showing variable name, proxy used, unit of measurement, data source, and time period.

Table 1: Variable Descriptions

Codes	Name of Variable	Proxy/Unit	Source	Time period
COEM	Carbon Emissions	Co2 emissions (Kt)	World Bank	1990-2020
GDPPC	GDP Per Capita	GDP per capita (current US$)	World Bank	1990-2020
TINO	Technology Innovation	Patent applications, residents	World Bank	1990-2020
FDINV	Foreign Direct Investment	Foreign direct investment, net inflows (% of GDP)	World Bank	1990-2020
PDEN	Population Density	Population density (people per sq. km of land area)	World Bank	1990-2020
FDEV	Financial Development	Domestic credit to private sector (% of GDP)	World Bank	1990-2020

RECON	Renewable Energy Consumption	Renewable energy consumption (% of total final energy consumption)	World Bank	1990-2020

The econometric representation of the model is provided in Equation 2 as follows:

$$COEM_t = \alpha + \beta_1 GDPPC_t + \beta_2 TINO_t + \beta_3 FDINV_t + \beta_4 PDEN_t + \beta_5 FDEV_t + \beta_6 RECON_t + \varepsilon_t \quad (2)$$

In the model equation, the constant term is symbolized by α, and the coefficients of the explanatory variables are represented by β_1, β_2, β_3, β_4, β_5, and β_6 and variable are used after converting the series into log form. The error term is symbolized as ε_t, and the variable t represents the time period from 1990 to 2020. Descriptive statistics of the variables utilized in the study, are shown in the table 2, given below.Table 2 presents the descriptive statistics for the variables of the study:

Table 2: Descriptive Statistics of the Variables

	COEM	**GDPPC**	**PDEN**	**TINO**	**FDEV**	**FDINV**	**RECON**
Mean	124070.7	807.9110	224.4349	108.8387	21.40149	1.56E+09	49.11114
Median	121672.7	688.5006	226.1988	91.00000	22.31456	1.12E+09	47.96000
Maximum	202047.2	1620.743	294.7239	338.0000	28.73378	5.59E+09	58.09129
Minimum	59026.00	346.6685	149.7173	16.00000	14.68225	2.45E+08	42.09000
Std. Dev.	42144.67	405.1925	45.07955	91.57805	4.371632	1.41E+09	4.276169
Skewness	0.245686	0.591588	-0.100503	1.083672	-0.186495	1.558374	0.350247
Kurtosis	2.018909	1.991435	1.727227	3.329200	1.682836	4.972795	2.333004
Jarque-Bera	1.555149	3.122097	2.144624	6.207425	2.420636	17.57446	1.208452
Probability	0.459519	0.209916	0.342216	0.044882	0.298102	0.000153	0.546497

Sum	3846192.	25045.24	6957.481	3374.000	663.4462	4.82E+10	1522.445
Sum Sq. Dev.	5.33E+10	4925429.	60964.97	251596.2	573.3349	5.97E+19	548.5687
Observations	31	31	31	31	31	31	31

Source: Author's Calculation

To capture the short-term and long-term relationships among the variables, the study utilizes the Autoregressive Distributed Lag (ARDL) approach, initially introduced by Pesaran et al. (1997). In order to confirm the presence of cointegration within the model, the error correction version of the ARDL method (Pesaran et al., 2001) is employed, and its equation (3) is presented below.

$$\Delta COEM_t = \alpha_0 + \sum_{i=1}^{r} b_i \Delta COEM_{t-i} + \sum_{i=1}^{s} c_i \Delta GDPPC_{t-i} + \sum_{i=1}^{u} d_i \Delta TINO_{t-i} + \sum_{i=1}^{p} e_i \Delta FDINV_{t-i} + \sum_{i=1}^{q} f_i \Delta PDEN_{t-i} + \sum_{i=1}^{v} g_i \Delta FDEV_{t-i} + \sum_{i=1}^{h} h_i \Delta RECON_{t-i} + \delta_1 COEM_{t-1} + \delta_2 GDPPC_{t-1} + \delta_3 TINO_{t-1} + \delta_4 FDINV_{i-1} + \delta_5 PDEN_{i-1} + \delta_6 FDEV_{i-1} + \delta_7 RECON_{i-1} + \varepsilon_t \quad (3)$$

Equation 3 introduces the operator Δ as the first difference, and it includes short-run dynamics represented by the bi, ci, di, ei, fi, gi, and hi. While, long run coefficients are shown as long-run coefficients δ1, δ2, δ3, δ4, δ5, δ6, and δ7. On the other hand, the long-run coefficients of the model are determined by employing equation (Eq. 4) within the framework of the ARDL approach.

$$COEM_t = \alpha_0 + \sum_{i=1}^{r} \beta_1 COEM_{t-i} + \sum_{i=1}^{s} \beta_1 GDPPC_{t-i} + \sum_{i=1}^{u} \beta_1 TINO_{t-i} + \sum_{i=1}^{p} \beta_1 FDINV_{t-i} + \sum_{i=1}^{q} \beta_1 PDEN_{t-i} + \sum_{i=1}^{v} \beta_1 FDEV_{t-i} + \sum_{i=1}^{h} \beta_1 RECON_{t-i} + \varepsilon_t \quad (4)$$

5. Results and Discussions

The study utilized Augmented Dickey Fuller (ADF) and Phillips Perron (PP) unit root tests to verify the stationarity of variables. The researchers applied the f-bounds test to examine the existence of co-integration in the model. The long-term and short-term impacts of explanatory factors have been captured using the ARDL and ECM methods. Causality linkages were explored using the Granger causality test. We present and discuss the findings from all the aforementioned methods below.

The sequence of econometric methods applied in the study is given in Figure 3.

Figure 3. Econometric Methods of the Study

ISSN: 2059-6588 (Print) | ISSN: 2059-6596 (Online)

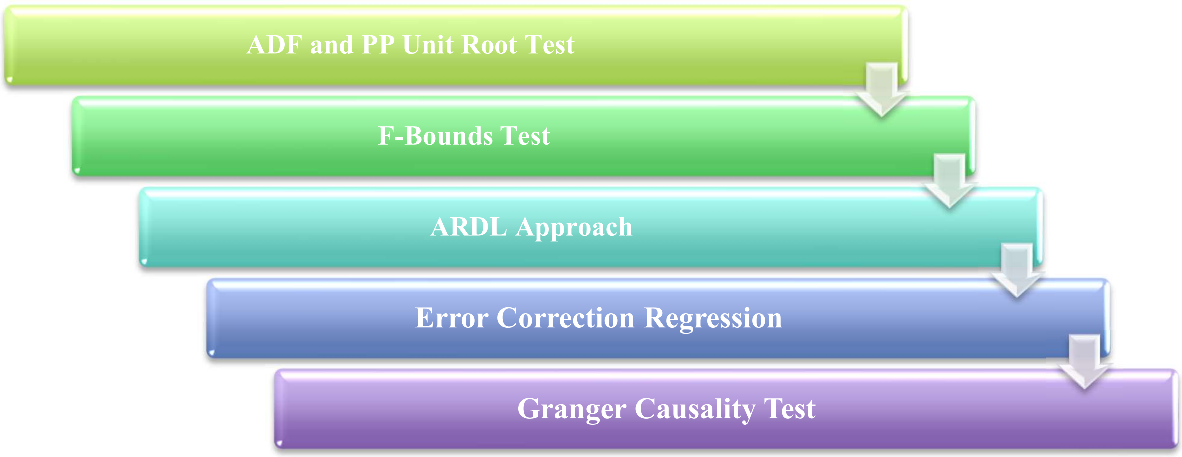


Table 2: Unit Root Tests

Variables	ADF Test			PP Test		
	Level	First Diff.	Stationary	Level	First Diff.	Stationary
COEM	-4.684*** (0.005)	-4.883*** (0.003)	I(0), I(1)	-2.347 (0.398)	-4.856*** (0.002)	I(1)
GDPPC	-2.634 (0.269)	-3.118** (0.037)	I(1)	-1.867 (0.646)	-3.862** (0.026)	I(1)
PDEN	-0.713 (0.961)	-3.700** (0.039)	I(1)	-0.592 (0.972)	-3.918** (0.021)	I(1)
TINO	-1.823 (0.668)	-6.828*** (0.000)	I(1)	-1.682 (0.734)	-6.922*** (0.000)	I(1)
FDEV	-1.683 (0.734)	-4.437*** (0.007)	I(1)	-1.938 (0.610)	-4.436*** (0.007)	I(1)
FDINV	-2.849 (0.193)	-3.724** (0.036)	I(1)	-2.225 (0.459)	-3.724** (0.036)	I(1)
RECON	-3.827** (0.021)	-5.198*** (0.001)	I(0), I(1)	-3.755** (0.022)	-5.197*** (0.001)	I(0), I(1)

Note: *, **, *** significant at 10%, 5% and 1% level respectively

The results of the unit root tests, namely the ADF and PP tests, as presented in Table 2, provide valuable insights into the stationary behavior of the variables employed in the regression analysis.

In the case of carbon emissions and renewable energy consumption, both tests indicate that these variables are stationary at both the level and the first difference. This suggests a stable, long-run relationship without any long-term trends or drifts. Short-term fluctuations, rather than fundamental shifts in the underlying structure, account for the observed changes in carbon emissions and renewable energy consumption. Conversely, the remaining variables, including technological innovation, foreign direct investment, financial development, GDP per capita, and population density, were found to be stationary only at the first difference.

The combination of variables exhibiting both stationary levels and first differences strengthens the suitability of the ARDL method for the regression analysis. The ARDL approach allows for the incorporation of variables with different stationary properties in the same model, accommodating the diverse characteristics of the variables under investigation. Furthermore, the consistency of results between the ADF and PP tests highlights the robustness and reliability of the findings. The agreement between these tests reinforces the validity of the conclusions drawn from the unit root analysis, providing confidence in the subsequent regression analysis.

The F-Bounds test confirmed the existence of cointegration in the model, with a significant F-statistic of 6.273, exceeding the critical values of 3.15 and 4.43, where ‘K’ represents the number of explanatory variables. This supports the alternative hypothesis and permits regression analysis to estimate the short-term and long-term linkages among the variables. Cointegration signifies a stable, long-term association between the variables, enabling a deeper understanding of their interactions over time.

Table 3: F-Bounds Test

F-statistic = 6.273***		**K = 6**
Critical Value Bounds		
Significance	**Lower Bound**	**Upper Bound**
10 percent	2.12	3.23
5 percent	2.45	3.61
2.5 percent	2.75	3.99
1 percent	3.15	4.43

Note. *** shows significant at 1% level

Table 4: ARDL Long-Term Estimates

Dependent Variable = COEM				
Variables	**Coefficients**	**Standard Error**	**t-Statistics**	**Prob.**
GDPPC	-0.053084	0.019717	-2.692345	0.0209**

FDEV	-0.224492	0.019608	-11.449003	0.0000***
FDINV	0.059494	0.005924	10.043106	0.0000***
TINO	0.017027	0.007282	2.338317	0.0393**
PDEN	0.794246	0.044922	17.680474	0.0000***
RECON	-1.589081	0.137922	-11.521605	0.0000***
C	13.246479	0.845283	15.671063	0.0000***

Note: *, **, *** significant at 10%, 5% and 1% level respectively

The findings from the ARDL analysis show valuable insights into the relationship between various independent variables and environmental degradation, as measured by carbon emissions in Pakistan (presented in Table 4). Firstly, higher GDP per capita is associated with lower environmental degradation, suggesting that economic prosperity promotes the adoption of cleaner technologies and environmental regulations, leading to reduced carbon emissions and a matching outcome, as revealed by Mansoor and Sultana (2018). Additionally, the study reveals that financial development has an inverse influence on environmental degradation in Pakistan. This implies that a well-developed financial sector enables investments in cleaner technologies and sustainable practices, contributing to a decrease in carbon emissions. Aljadani, (2022). Technological innovation also demonstrates a positive impact in Pakistan, indicating that advancements in technology can drive more efficient and environmentally friendly production processes, further reducing environmental degradation (Adebayo et al., 2021). In contrast, FDI shows a direct effect on environmental degradation in Pakistan, indicating that the country may face challenges in managing its environmental impact as it attracts FDI. This could be due to the potential arrival of industries with lower environmental standards or increased resource exploitation to meet foreign demands (Singhania & Saini, 2021). However, it is worth noting that effective environmental regulations and sustainable policies can help mitigate the positive influence of FDI on environmental degradation in Pakistan. Moreover, population density exhibits a positive influence on environmental degradation in Pakistan, suggesting that densely populated areas tend to have higher carbon emissions. This is likely due to the increased resource consumption and energy demand associated with higher population densities (Solarin, 2020). The study reveals a correlation between higher renewable energy consumption and reduced environmental degradation in Pakistan. This underscores the significance of transitioning to renewable energy sources as a means to mitigate carbon emissions and promote environmental sustainability in the country (Sharif et al., 2019).

Short-run linkages among the variables are captured through the error correction method, as shown in Table 5. The results obtained through the error correction method of the ARDL approach provide significant insights into the relationship between the variables and carbon emissions. The value of the error correction term showed 73.2 percent convergence in the model in the short run. The high R-squared value of 0.954 suggests that the model explains 95.4% of the total variation, indicating a strong fit. The low standard error of regression, 0.015, signifies precise estimates. The included variables explain 88.2% of the variation in carbon emissions, as indicated by the adjusted R-squared value of 0.882, considering the number of variables and observations, highlighting a robust relationship. The F-statistic's probability of 0.000, below 0.01, indicates the model's statistical significance, suggesting that at least one variable significantly impacts carbon emissions. The Durbin-Watson statistic of 2.629 falls within the acceptable range, indicating no significant autocorrelation. Additionally, the F-statistic of 13.345 reveals the joint significance of short-run coefficients, emphasizing their significant impact on carbon emissions.

Table 5: Short Run Estimates of Error Correction Model

Dependent Variable: COEM				
Selected Model: ARDL(2, 0, 2, 2, 1, 2, 2)				
Sample: 1990-2020				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
D(COEM(-1))	0.548578	0.302874	1.811244	0.0975
D(GDPPC)	-0.133144	0.051412	-2.589749	0.0251**
D(FDEV)	-0.248423	0.058651	-4.235596	0.0014***
D(FDEV(-1))	0.142981	0.082217	1.739072	0.1099
D(FDINV)	0.056888	0.011064	5.141613	0.0003***
D(FDINV(-1))	-0.037097	0.016496	-2.248908	0.0460**
D(TINO)	0.004469	0.016560	0.269856	0.7923
D(PDEN)	13.294481	4.345629	3.059277	0.0109***
D(PDEN(-1))	-7.518977	2.133599	-3.524082	0.0048***
D(RECON)	-1.372773	0.197226	-6.960401	0.0000***
D(RECON(-1))	0.746762	0.481263	1.551673	0.1490
CointEq(-1)	-0.732430	0.058970	-15.671063	0.0000***
R-squared	0.953754	**S.E. of regression**	0.015508	
Adjusted R-squared	0.882284	**Prob(F-statistic)**	0.000052	

Durbin-Watson stat	2.629390	**F-statistic**	13.34474

Note: *, **, *** significant at 10%, 5% and 1% level respectively

We used the Granger causality test to estimate the causal linkage between carbon emissions and each independent variable. The results of this analysis are summarized in Table 6. The outcomes indicate that carbon emissions exhibit a unidirectional linkage with GDPPC, FDEV, and RECON. Furthermore, carbon emissions exhibit a bidirectional relationship with both PDEN and TINO. However, no causal linkage is detected between carbon emissions and FDINV.

Table 6: Granger Causality Analysis

Pair of variables	**F-Statistic**	**Probability**	**Causality**
GDPPC to COEM	1.24500	0.3059	Unidirectional
COEM to GDPPC	2.97560	0.0701*	
FDEV to COEM	1.86870	0.1761	Unidirectional
COEM to FDEV	2.91118	0.0738*	
FDINV to COEM	1.54094	0.2346	No Causality
COEM to FDINV	0.89162	0.4231	
PDEN to COEM	7.29561	0.0033***	Bidirectional
COEM to PDEN	12.8308	0.0002***	
TINO to COEM	3.51281	0.0459**	Bidirectional
COEM to TINO	13.4651	0.0001***	
RECON to COEM	2.38743	0.1133	Unidirectional
COEM to RECON	3.71353	0.0393**	

Note: *, **, *** significant at 10%, 5% and 1% level respectively

Findings of the stability tests including CUSUM and CUSUM square depicted the stability of the coefficients of the model. Outcomes of both stability tests are shown in figure 4 and figure 5.

Figure 4.CUSUM Test

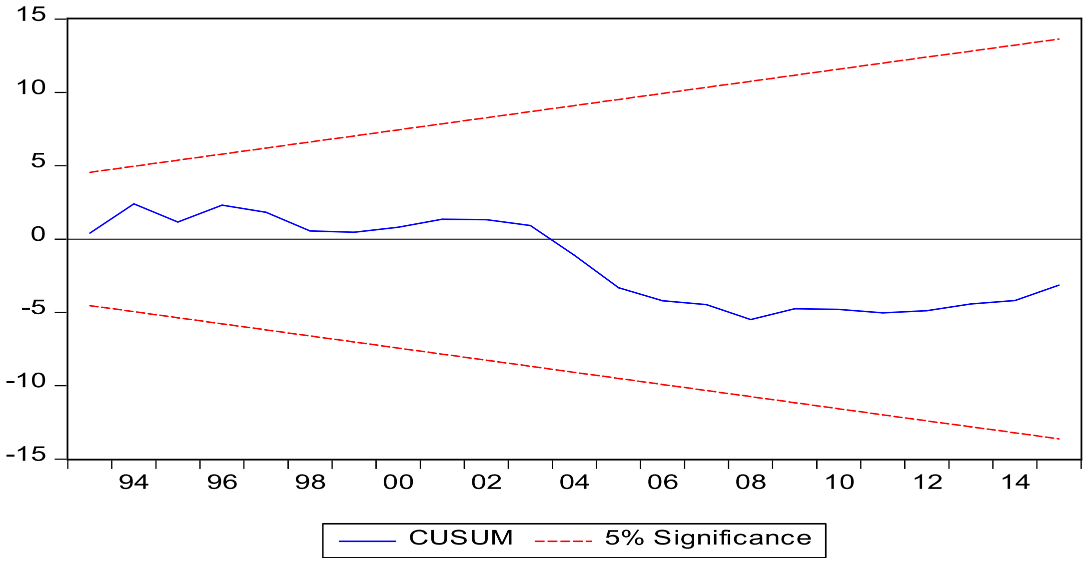
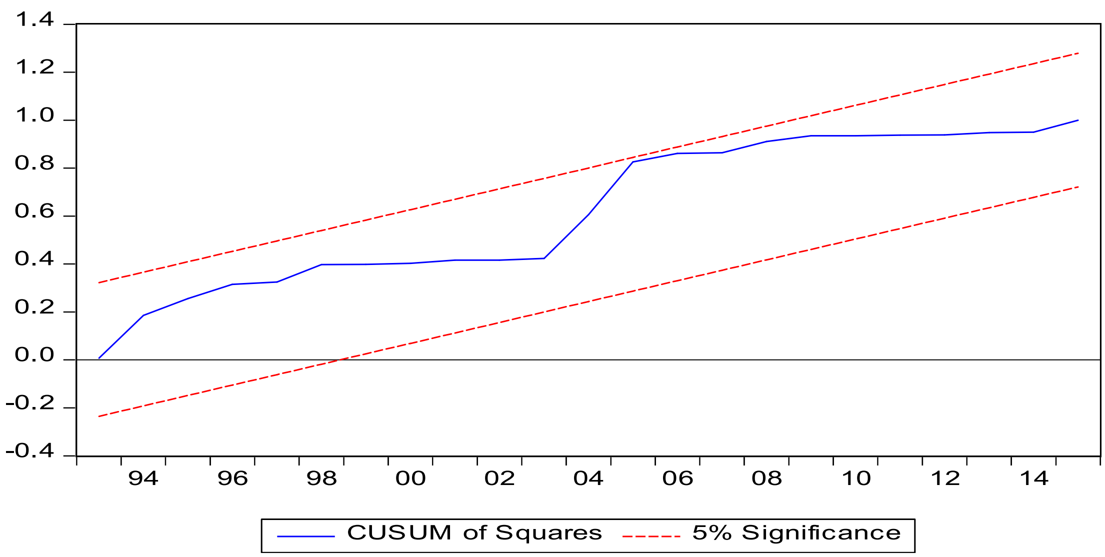


Figure 5. CUSUM Square Test



6. Conclusion and Policy Recommendations

To tackle the alarming issue of environmental degradation, the present study has examined key responsible factors of carbon emissions in Pakistan for the time period of 1990–2020. The F-bounds test provided evidence of cointegration in the model, suggesting a long-term linkage between the variables. The findings from the ARDL approach revealed several important insights. The findings from the ARDL approach revealed that GDP per capita negatively impacts environmental degradation, indicating a link between economic growth per person and lower carbon emissions. This highlights the importance of sustainable economic development policies that promote resource efficiency and environmental conservation. Secondly, the study found that financial development negatively impacts environmental degradation. This suggests that a well-developed financial sector, characterized by efficient allocation of resources and investments in environmentally friendly projects, can contribute to reducing carbon emissions. Thirdly, the study found that technological innovation directly influences environmental degradation. This underscores the need for policies that foster green innovation and promote the adoption of clean technologies to mitigate the adverse environmental effects of economic activities. In addition, researchers discovered that population density positively contributes to environmental degradation. This implies that rapid urbanization and population growth can exacerbate environmental challenges. Therefore, urban planning strategies that prioritize sustainable infrastructure, efficient resource management, and environmentally conscious practices are essential. Lastly, renewable energy consumption was found to have an inverse influence on environmental degradation. This emphasizes the significance of transitioning towards renewable energy sources to reduce carbon emissions and promote sustainable energy practices.

Based on the findings of the study, we propose the following policy suggestions for Pakistan to reduce environmental degradation and carbon emissions: Firstly, to address the negative impact of GDP and financial development on carbon emissions, the government should prioritize policies that promote sustainable and eco-friendly industries, encouraging a shift towards green economic growth. Secondly, to leverage the positive relationship between FDI and carbon emissions, Pakistan should actively attract foreign investors seeking environmentally responsible projects, providing incentives and support to drive green investments. Thirdly, to capitalize on the positive impact of technological innovation on carbon emissions, the country must invest in the research and development of clean technologies and foster an environment that supports the implementation of energy-efficient solutions. Furthermore, to address the positive correlation between population density and carbon emissions, the country should implement smart urban planning initiatives that emphasize efficient public transportation and green infrastructure within cities. Furthermore, to enhance the negative relationship between renewable energy consumption and carbon emissions, the government should prioritize the adoption and expansion of renewable energy sources through favorable policies and incentives for consumers and businesses. By implementing these individual policy measures while strengthening environmental regulations, Pakistan can work towards mitigating environmental degradation and promoting a more sustainable future.

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