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Title: **Re-thinking Progress: How Financial Growth, Renewable Energy, and Innovation Shape Pakistan's Carbon Emissions**

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Re-thinking Progress: How Financial Growth, Renewable Energy, and Innovation Shape Pakistan's Carbon Emissions

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Abstract

The long-term viability of development strategies hinges on achieving a harmonious balance BETWEEN economic growth and environmental protection. The current research aimed to explore the relationships of financial development (FD), renewable energy consumption (REC), and technological innovation (TI) with carbon emissions (CO_2) in Pakistan. The Dynamic Ordinary Least Square (DOLS) method was employed to analyze the relevant data for the time period (1991-2023) that was derived from World Development Indicators (WDI) and World Intellectual Property Organization (WIPO). The results of Fully Modified Ordinary Least Square (FMOLS) and Canonical Correlation Regression (CCR) confirmed the robustness of the model. The results of the analysis indicated that the FD was positively related to CO_2, indicating that a 1% increase in FD led to 0.10% increase in CO_2 emissions (statistically significant at the 1% level). The REC had a significant positive impact on environmental quality, that is, decreasing CO_2 emission by 1.44% (statistically significant at the 1% level). Whereas, the TI had a negative effect on environmental quality. A 1% increase in TI contributed to a 0.093% increase in CO_2 emissions (statistically significant at the 5% level). It was concluded that financial institutions supported industrial expansion along with increased consumption of energy-intensive goods and implementation of carbon-intensive projects. Innovations appeared to be focused on energy-intensive sectors rather than green technologies. This might be due to a dirty innovation bias, measurement issues, or delayed environmental benefits. It is recommended that the government should incentivize green energy initiatives and eco-friendly technologies to mitigate the harmful effects of

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environmental degradation in Pakistan. A shift towards renewable energy sources should be promoted to stabilize the environment in the long run.

***Keywords*:** broad money, carbon footprint, dynamic ordinary least square, environmental sustainability, innovative technologies, non-renewable energy

Introduction

Climate change is considered as a pressing global concern at least since last three decades. The continuous increase in carbon emissions (CO_2) due to rising economic activities has significant implications for the environment (Khan et al., 2022; Onofrei et al., 2022; Wu & Wan, 2024). Sustainable energy solutions, innovative technologies, and financial development (FD) have an important role in shaping global climate outcomes. The alarming rise in average temperatures and rapid melting of glaciers have devastating consequences, particularly in the developing countries.

Climate change is a big challenge for Pakistan that causes usual climatic happenings, water scarcity, and severe impacts on agriculture and biodiversity. Globally, the climate risk is assessed by measuring the impact of extreme weather events on countries and thereby these countries are ranked based on economic and human losses. Pakistan has been ranked 5th in the world amongst countries badly affected by climate change. Between 1999 and 2018, Pakistan incurred significant economic losses, totalling USD 3.8 billion, due to the occurrence of 152 episodes of extreme weather (Eckstein et al., 2018). In recent decades, Pakistan has grappled with pressing environmental concerns, notably a marked rise in CO_2 emissions. In 2013, Pakistan's share of global CO_2 emissions was 0.69% (International Energy Agency [IEA], 2020). Pakistan's carbon footprint increased significantly, with CO_2 emissions reaching 320.7 million tons in 2013, representing a more than twofold increase from the 150.66 million tons recorded in 1990.

Pakistan has endorsed two pivotal international accords: the Paris Agreement and the Kyoto Protocol. By ratifying these agreements, Pakistan has committed to meeting specific targets aimed at curbing greenhouse gas emissions. Pakistan was mandated by the Kyoto Protocol in the 1990s to cut its greenhouse gas emissions up to 5%. Pakistan has also approved the Doha Amendment in 2012 which shows Pakistan’s seriousness for saving the environment. Wang et al. (2019) has described that the adoption of the

Paris Agreement marked a significant turning point for nations which were heavily reliant on fossil fuels. A critical question arises about Pakistan's progress towards the achievement of agreed actions for preserving the environment and subsequent reduction in CO_2 emissions in Pakistan.

Pakistan can undertake a committed action plan for the reduction of CO_2 emissions by investigating the effects of sustainable energy solutions, driving technological innovation, and pursuing economic growth. However, such action plan can be implemented only if an appropriate investment is made for environmentally sustainable financial practices. This comprehensive approach can be achieved by diversifying the energy mix with renewables, such as solar and wind power, and making use of cutting-edge technologies. The implementation of green financing initiatives which support eco-friendly projects and industries can effectively mitigate CO_2 emissions.

The FD can significantly influence the natural environment. As a developing country, Pakistan is facing severe environmental challenges. The growth of FD in developing countries usually leads towards fast industrialization and urbanization. Since these developing countries lack advanced technology and have limited renewable energy, this growth often causes more CO_2 emissions and is harmful to the environment (Jiang & Ma, 2019; Shoaib et al., 2020). On the other hand, the growth of the financial sector in these developing countries may not be able to support the use of modern, eco-friendly technologies. Therefore, unplanned and non-targeted growth of financial sector might even slow down efforts to cut CO_2 emissions. If developing countries do not invest in green technology and fail to take focused action in this regard, then the financial growth may keep supporting such technologies which are outdated and polluting the environment. This underlines the importance of strategically planned FD that focuses only on protecting the environment and helps shift industry towards cleaner technologies.

Linking economic development with eco-friendly practices is highly important. This is because the achievement of any country's prosperity now depends on protecting its natural resources. For resilient and a thriving planet, a strategically planned economic growth is highly important that does not draw on environmental conservation. By including sustainable practices in their economic plans, countries can grow and develop in the long-term. Moreover, this may also save the natural resources for future generations. This harmonious relationship between economy and environment is essential to achieve a sustainable future. The long-term viability of development strategies depends on whether economic growth happens by damaging the environment or by properly taking environmental costs into account.

The financial sector has experienced rapid growth since the inception of Pakistan. Over the past three decades, Pakistan's monetary reserves have increased approximately 28 times, from 3,350 billion rupees in 1990 to 94,610 billion rupees in 2019. The country's rapid financial growth has raised significant concerns regarding its environmental sustainability and potential long-term ecological implications (Government of Pakistan [GOP], 2024). According to the Sustainable Development Goals (SDGs) Report 2024, Pakistan significantly lags behind in achieving most of the SDG's targets by the end of the decade. Ranked 137th out of 166 analysed countries, Pakistan's progress is concerning with most of the indicators either off-track or stagnating. Conversely, research indicates that Pakistan has made progress towards SDG 13, which focuses on climate change (Sachs et al., 2024). Similarly, during the past three decades, the rapid increase in fossil fuel consumption has significantly impacted the environment worldwide, particularly in developing countries. Countries worldwide are increasingly adopting cleaner and renewable energy sources (Sohag et al., 2019). The pressing issues of climate change and environmental sustainability have brought attention to the need for accelerated development and utilization of renewable energy sources (Sharif et al., 2021).

Pakistan lies within one of the sunniest parts of the world and is well-positioned to leverage solar energy technology due to extended sunshine hours. Due to its geographical location, Pakistan receives ample sunlight which is a highly accessible and plentiful resource to generate solar energy. The country receives an average of 200-250 watts of radiation per day, approximately 1,500-3,000 hours of sunshine or 1.9-2.3 MWh/m per year. This energy source is particularly abundant in Baluchistan which is the largest province in Pakistan with respect to its land area. Similarly, the potential for solar energy has been explored by Khalil and Zaidi (2014). They estimated that Pakistan's solar energy potential was among the top countries globally which had an average daily worldwide sunlight of 19-20 MJ/day and a yearly average sunshine time frame of 8-8.5 hours per day.

In addition to solar energy, Pakistan also has a significant potential to produce electricity from biomass residues. The country generates millions of tonnes of solid biomass per year from the wastes of crops, such as maize cobs, rice husk, wheat, and cotton stalks. Experts suggest that small and medium-sized enterprises (SMEs) can construct their own 500 KW to 550 KW biomass projects to meet their energy and heating needs. The sugar industry, in particular, has the potential to produce over 1,000 MW of power from biomass. To accelerate the development of bagasse-derived power, a co-generation policy through the Private Power Infrastructure Board (PPIB) has been formulated in Pakistan.

Pakistan's northern region is also rich in hydro power resources. Apart from micro hydroelectric plants, numerous locations in the highlands feature naturally produced, controllable waterfalls. The recoverable potential for micro-hydro power (MHP) up to 100 KW is approximately 300 MW. Furthermore, the Pakistan Meteorological Department (PMD) initiated an assessment in 2002 to evaluate wind resources in the southern regions. Anemometers were installed on meteorological masts at heights of 10 and 30 meters. Despite Pakistan's significant clean energy potential, the connection between low-carbon energy use and environmental protection remains under explored, warranting a closer examination.

The successful attainment of SDGs is heavily reliant on technological innovation, which enables the adoption of eco-friendly practices and clean energy adaptations. Innovative technology can enable the countries to make transition towards more resource-efficient systems which minimize detrimental environmental impacts and promote long-term sustainability. Various studies have shown that innovation-related initiatives can enhance the quality of natural environment (Churchill et al., 2019; Huang et al., 2020). However, other studies suggest that innovation-related activities can also have negative environmental impacts (Dauda et al., 2019; Ganda, 2019; Pervaiz et al., 2025). In developing countries, such as Pakistan, the adoption of technological innovations often leads towards increased energy which is largely fulfilled by relying on fossil fuel combustion. The dependence on fossil fuels amplifies CO_2 emissions and worsens environmental deterioration. This, in turn, poses significant threats to ecosystems, biodiversity, and human health. To mitigate this, the exploration of alternative energy sources, investment in renewable technologies, and implementation of sustainable practices to reduce carbon footprint is required while still driving economic growth and development.

Despite the existing literature, further country specific investigation is required to study how the economic development, green energy, and innovative technologies impact the emission of CO_2 to the environment. Therefore, the instant study aimed to estimate the dynamic impact of FD, renewable energy consumption (REC), and technological innovation (TI) on CO_2 emissions for the time period (1991-2023). Based on literature review, the following research hypotheses were tested:

H_1: FD has a positive and significant effect on CO_2 emissions in Pakistan.

H_2: REC has a negative and significant effect on CO_2 emissions in Pakistan.

H_3: TI has a negative and significant effect on CO_2 emissions in Pakistan.

The study employed unit root tests, such as Augmented Dickey-Fuller (ADF), Dickey-Fuller (DF), and Phillips-Perron (PP) The DOLS model was used to examine the relationships and long-term effects between the variables. Subsequently, the FMOLS and CCR models were estimated for confirmation of the results received from the DOLS model. This research offered clear recommendations to policymakers in order to create targeted policies that support green energy adoption and FD.

Literature Review

The association between economic development, the use of green energy, and innovative technologies has been extensively explored. Studies show that this relationship is not simple because the economic development can either support or block sustainability. For instance, Raihan and Tuspekova (2022) undertook a research in the context of Kazakhstan and Investigated the complex linkages among economic expansion, renewable energy usage, technological advancements, and environmental protection. They employed DOLS analysis on a data set covering the time period (1996-2018). As a result, a positive relationship was explored between consumption of fossil fuel, economic development, and carbon foot print. In contrast, it was concluded that TIs and green energy use had a significant negative impact on the emission of CO_2.

Imran et al. (2022) studied conservation of natural resources in the QUAD countries, that is, Australia, India, Japan, and the United States. They analysed the time period from 1991-2021. The study concluded that the innovative technologies and sources of green energy production improved environmental sustainability. However, the FD and traditional sources of energy worsened it. In a related study, Saliba et al. (2022) examined the patterns of CO_2 emissions in China for three decades since 1990 up to 2019. Their findings revealed that economic development and green energy helped reduce the emission of CO_2. Whereas, remittances and globalization had a counter-intuitive negative impact, suggesting a more complex relationship between these variables. These results contributed in the understanding of environmental sustainability in China and underlined the need for effective policy implementation to mitigate emissions.

A study by Raihan et al. (2022) investigated the dynamic relationships existing between CO_2 emissions, economic expansion, green energy adoption, and technological advancements in Bangladesh. They analysed the time period from 1980-2019 and used DOLS technique. Their study revealed that economic development led to higher levels of CO_2 emissions and underscored the environmental challenges which often accompany economic expansion. In contrast, TIs and the use of clean energy were identified as important factors to promote environmental sustainability. These studies suggested that investment in these areas reduced the harmful effects on the environment by the financial growth. They emphasized that sustainable solutions and green energy needed to be mainstreamed in development planning. In another study, Ullah et al. (2023) investigated the interconnected association of TI, financial growth, and climatic sustainability in the context of the world's top 14 financially developed economies. By analyzing the data ranging from 1990-2018, it was explored that financial growth had an adverse impact on climatic sustainability while trade openness, globalization, use of renewable energy, and innovative technology had positive effects.

Anser et al. (2021) explored the linkage of energy consumption, CO_2, and economic development in the selected South Asian countries throughout 1985 - 2019. The data on the study variables was gained from World Bank. EKC framework and FMOLS methods were applied. They identified that the environment quality was worse in South Asian countries. The study showed a bi-directional causality between energy consumption and economic development, indicating interdependence of these two variables, that is, increased energy consumption drove economic growth and vice versa. This interrelationship highlighted the need for sustainable energy solutions which supported economic development while minimizing environmental impacts. Villanthenkodath and Mahalik (2022) conducted an investigation into the nexus of technological advancements with climate sustainability in India. Using the ARDL technique, the study uncovered a long-run relationship among the variables. Notably, the analysis revealed a U-shaped correlation between CO_2 emissions and inward remittances and recommended that initially, remittances might be associated with lower emissions, however, beyond a certain threshold, they contributed to increased emissions. This complex relationship highlighted the need for thorough understanding and policy implementation regarding remittances and environmental sustainability.

Djellouli et al. (2022) examined the environmental sustainability across African nations. Their analysis of 20 selected African countries revealed a positive association between emissions of CO_2 and most independent variables, for instance conventional form of energy use, FD, and trade with notable exception of renewable energy. This suggested that higher use of green energy was linked with a decrease in CO_2. In contrast, the other variables exhibited a positive relationship with emission of CO_2 which led to the conclusion that these variables contributed to increased emissions. These findings underscored the use of renewable energy to mitigate the loss to the climate in African countries.

Awosusi et al. (2022) studied the effects of economic growth on environmental conservation in Colombia. They considered CO_2 emissions, Gross Domestic Product (GDP), green energy, global aspect of world economies, and total rental value of natural resources. They used data from 1979-2017 that was obtained from the World Development Indicators (WDI) and British Petroleum database. The study employed multiple econometric models, including FMOLS, DOLS, and ARDL. The analysis showed a positive linkage between economic development and emission of CO_2. This suggested that FD increased CO_2 potentially due to enhanced economic activity and energy consumption. It was indicated that GDP adversely impacted the environment. However, the empirical investigation also found that low-carbon energy use and globalization decreased CO_2 emissions. Zaman and Moemen (2017) undertook a research to find the relationships of CO_2 with energy and economic growth. This study explored diverse viewpoints, that is, Pollution Haven Hypothesis, effect of population growth on emissions, Environmental Kuznets Curve hypothesis, and disparity between emissions and HDI, with a distinction based on country income levels. Using data from 1975-2015 obtained from the WDI and International Monetary Fund (IMF), the study supported the energy-based emission, sectoral expansion emission, EKC hypotheses in various countries, while the HDI and PHH hypotheses failed to support the results.

Data and Analytical Methods

The study variables were investigated using DOLS co-integration method which was presented by Pesaran and Shin (1995) and later, improved by Pesaran et al. (2001). The analysis involved the following indicators:

- CO_2 emissions taken as estimation of environmental degradation (Awosusi et al., 2022; Villanthenkodath & Mahalik, 2022)
- Broad money (current LCU) as a measure for FD (Ullah et al., 2023; Wu & Wan, 2024)
- Renewable energy share in total energy mix (Djellouli et al., 2022; Saliba et al., 2022; Zaman & Moemen, 2017)
- TIs measured by total patent applications (Fei et al., 2014; Raihan & Tuspekova, 2022; Tang & Tan, 2013). An increase in patent applications indicated the adoption of new technologies in industries and agriculture.

The annual values of data for the selected variables were collected from the WDI and World Intellectual Property Organization (WIPO) for the time period 1991-2023.

Table 1

Variables Used in the Study

Notation	Variables	Measurements	Data Sources (Indicator Code)
CO_2	Ecological Footprint	Metric tons per capita	WDI (EN.ATM.CO2E.PC)
FD	Financial Development	Broad Money measured in current Local Currency Unit (LCU)	WDI (FM.LBL.BMNY.CN)
REC	Renewable Energy	Renewable energy share in total energy mix	WDI (EG.FEC.RNEW.ZS)

Notation	Variables	Measurements	Data Sources (Indicator Code)
TI	Technological Innovation	Annual patent applications (including residents and non-residents) filed in Pakistan	WIPO (Data Series - A9)

The model used in the instant research is given as following:

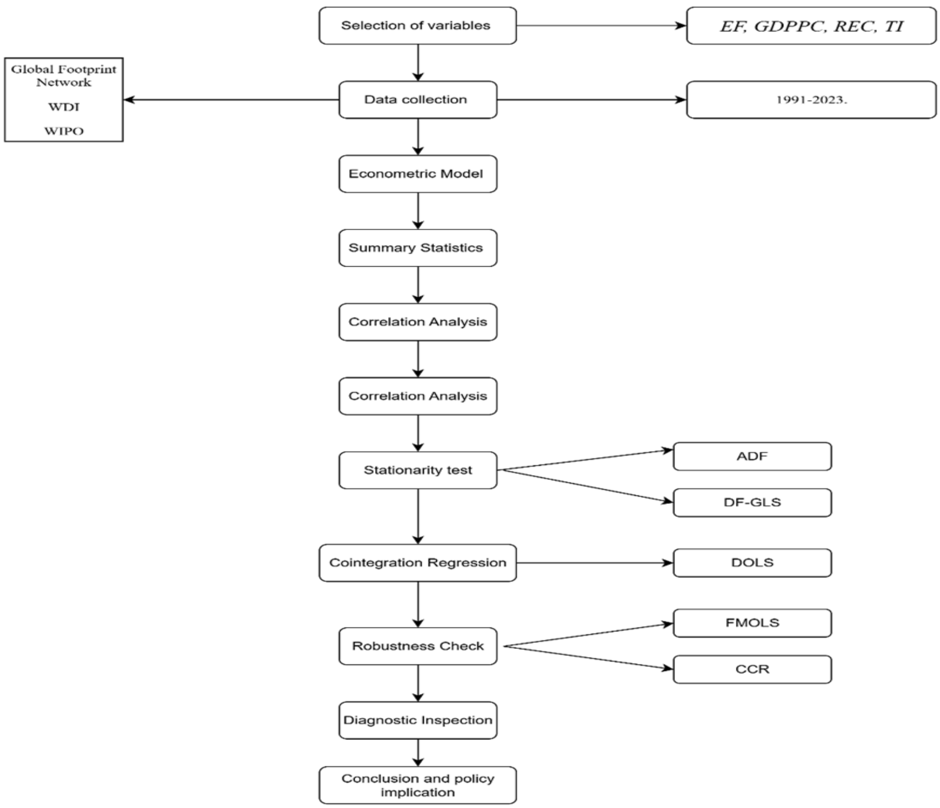
$$CO_2 = f\,(FD, REC, TI,) \quad (1)$$

The regression model was specified as following:

$$LnCO_{2t} = \gamma_0 + \gamma_1 LnFD_t + \gamma_2 LnREC_t + \gamma_3 LnTI_t + \mu_t \quad (2)$$

Figure 1

Flow Chart of Analytical Techniques



The variables of $LnCO_2$, LnFD, LnREC, and LnTI in the above equation are logarithmic form of the study variables of CO_2, FD, REC, and TI. All the variables were transformed into natural logarithmic form to stabilize the variance, normalize the data distribution, and interpret the coefficients as elasticities. However, the t represents the time series and μ is noise.

CO_2 is a dependent/response variable, while FD, REC, and TI are independent/ explanatory variables. The proxies for selected variables are mentioned in Table 1. The symbols γ_0 is intercept, while γ_1, γ_2, γ_3, and γ_4 are regression parameters of the model and subscript (*t*) indicating the time series "t".

Figure 1 presents the analytical framework adopted in this study which delineates a step-by-step approach to investigating the dynamic association amongst the variables.

Results and Discussion

Stationarity of Data

This study employed the ADF test which was presented by Dickey and Fuller (1979) to look for the unit root problem in the study variables. Multiple unit root tests are utilized to verify the possibility of unit roots in the data (Raihan & Tuspekova, 2022). The Dickey-Fuller Generalized Least Square (DF-GLS) test proposed by Elliott et al. (1992) and the P-P test developed by Phillips and Perron (1988) are also applied to cross-validate the results. The ADF test is typically formulated as following:

$$\Delta y_t = \beta_1 + \beta_{2t} + \beta_3 y_{t-1} + \beta_4 E \Delta y_{t-1} + \varepsilon_t \tag{3}$$

While the general form of P-P test is:

$$y_t = \alpha + p y_{t-1} + \mu_t \tag{4}$$

The series are found to be integrated at mixed orders of level and first difference which supports the application of the DOLS cointegration technique as compared with traditional cointegration methods (Raihan & Tuspekova, 2022).

Table 2
Results of Unit Root Tests

Logarithm form of the variables		LnCO2	LnFD	LnREC	LnTI
ADF	Level	-1.8083 (0.3699)	-0.6862 (0.8358)	-3.2208 (0.0082)	0.1861 (0.9674)
	1st Difference	-4.2650 (0.0028)	-3.8947 (0.0073)	-7.2600 (0.0000)	-6.7947 (0.0000)
DF-GLS	Level	-0.8983 (0.3759)	-0.8185 (0.4202)	-3.1279 (0.0079)	0.317 (0.7533)
	1st Difference	-4.4990 (0.0001)	-2.3236 (0.0163)	-5.1428 (0.0000)	-6.396 (0.0000)
P-P	Level	-1.8124 (0.3680)	-1.0789 (0.7118)	-3.2208 (0.0082)	0.833 (0.9931)
	1st Difference	-4.5649 (0.0010)	-8.1584 (0.0000)	-7.2784 (0.0000)	-6.802 (0.0000)

Table 2 shows the outputs of unit root tests which were used to confirm the stationarity of the time series data. The outcomes indicated whether the variables were stationary or non-stationary and informed the choice of subsequent econometric techniques. The instant study used ADF, P-P tests, and DF-GLS approaches to address the unit root problem. The analysis revealed that the LnREC had stationarity in both its original form and after taking first differences. In contrast, $LnCO_2$, LnFD, and LnTI were not stationary at levels, however, became stationary at their first differences which was confirmed by the ADF, P-P tests, and DF-GLS. The unit root test results indicated a mix of integration orders, with some variables displaying stationarity at level [I(0)] and others achieving stationarity after first differencing [I(1)]. It was worth noting that the data series became stationary mostly at the first difference [I(1)], with no variable requiring higher-order differencing. The observed integration order guided towards the suitability of DOLS model to examine the long-run relationships amongst the study variables.

DOLS Model and Robustness Check

The current study utilized the DOLS model of cointegration which required all variables to be integrated at mixed orders with no series integrated at the second difference. The Johansen cointegration test confirmed the existence of at least one cointegrating relationship among the variables. It validated the application of DOLS model for the estimation of long-run coefficients. The DOLS model was chosen over alternative cointegration methods because it mitigated endogeneity concerns. This model gave robust standard errors by utilizing a covariance matrix. One lead and one lag of the first-differenced regressors were used in this model which were selected based on the Schwarz Information Criterion (SIC) and model stability checks. This approach helped solve problems related to endogeneity and serial correlation and ensured reliable long-run estimates. The model also allowed dependable testing of the variables' significance, as the standard deviation of DOLS estimators followed a normal asymptotic distribution (Raihan et al., 2022).

The robustness of the DOLS estimators was confirmed by applying FMOLS and CCR models. The FMOLS regression, corrected for serial correlation and endogeneity, provided efficient and unbiased estimates of the long-run relationships. The CCR regression introduced by Park (1992) transformed the data and used only the stationary part of the cointegration model. By removing the correlation between the error term and the regressors at zero frequency, the CCR method produced estimates. Such estimates were completely free from serial correlation. The long-run coefficients were then calculated using both the FMOLS and CCR techniques. The econometric model is presented as following:

$$\Delta LnCO2_t = \pi_o + \pi_1 LnCO2_{t-1} + \pi_2 LnFD_{t-1} + \pi_3 LnREC_{t-1} + \pi_4 LnTI_{t-1} + \sum_{i=1}^{\rho} \beta_1 \Delta LnCO2_{t-1} + \sum_{i=1}^{\rho} \beta_2 \Delta LnFD_{t-1} + \sum_{i=1}^{\rho} \beta_3 \Delta LnTI_{t-1} + \varepsilon_t \quad (5)$$

Table 3 gives the output of the DOLS model that was calculated as per Equation 5. Keeping other variables constant, the average long-run coefficient of LnFD was found to be positive and statistically significant at the 1% level. This meant that a 1% increase in financial growth led to a 0.10% rise in CO_2 emissions. These results suggested that financial growth led to higher CO_2 emissions in Pakistan. This could be due to increased industrial development and economic activities which were associated burning of fossil fuels. These findings were consistent with previous studies (Atif et al., 2024; Jiang & Ma, 2019; Khan et al., 2020; Shoaib et al., 2020).

The analysis also showed that LnREC had a negative and statistically significant impact on CO_2 in the long run. The coefficient was significant at the 1% level and indicated that a 1% increase in REC resulted in a 1.44% reduction in CO_2 emissions. These findings were supported in literature by Zaidi et al. (2018) and Amin et al. (2023). In contrast, LnTI was found to increase CO_2 emissions significantly in the long run. The results showed that a 1% increase in LnTI was associated with a 0.09% rise in CO_2 emissions, and the LnTI coefficient was statistically significant at the 5% level. This indicated that TI in Pakistan had not been environmentally friendly and contributed to higher CO_2 emissions. These results were consistent with Gao and Fan (2023) and Ali et al. (2022).

The diagnostic tests confirmed that the model was correctly specified and had a good fit. The values of R^2 ,that is, 0.9953 and Adjusted R^2 ,, that is, 0.9920 indicated that the model accounted for nearly 99% of the variation in the response variable. Furthermore, the F-statistic was observed to be 51.9865, with a probability of 0.0000, which suggested that the linear relationship between the response and the explanatory variables was significant. Furthermore, the Root Mean Square Error (RMSE) was 0.002556, which was closer to zero and positive. This meant that the outputs of DOLS model perfectly matched with the data. The multicollinearity among the independent variables was assessed using the Variance Inflation Factors (VIF). All VIF values were below the commonly accepted threshold of 10 which indicated that multicollinearity was not a significant concern in the model.

Table 3

Results of DOLS: Response Variable LnCO$_2$

Variables	Coefficient	*SE*	*t*	*p*
LnFD	0.100110***	0.026377	3.795325	0.0014
LnREC	-1.449235***	0.298856	-4.84928	0.0004
LnTI	0.093526**	0.038161	2.452724	0.0253
C	6.123311	0.688056	8.899444	0.0000
R^2	0.995317			
Adjusted R^2	0.992012			
Standard error of regression	0.012261			
Long run Variance	0.000187			
F-Statistics	51.98653			
Prob (*F*-Statistics)	0.000000			
RMSE	0.002556			

The FMOLS and CCR models were used to cross-check and validate the results obtained from the DOLS model. The results of these models were presented in Tables 4 and 5, respectively. The outcomes of these models confirmed the robustness of the DOLS model and indicated consistent relationships between the variables. The FMOLS and CCR results showed that FD and TI had direct impact on CO_2 emissions. In contrast, REC had a negative and statistically significant relationship with CO_2. Additionally, the R^2 and adjusted R^2 values for both FMOLS and CCR models confirmed that the models were well-fitted.

Table 4

Output of FMOLS: Response Variable LnCO₂

Variables	Coefficient	*SE*	*t*	*p*
LnFD	0.106074***	0.028274	3.751619	0.0008
LnREC	-1.528852***	0.246690	-6.197499	0.0000
LnTI	0.081772**	0.038991	2.097173	0.0451
C	6.190844	0.595655	10.39334	0.0000
R^2	0.988106			
Adjusted R^2	0.986832			
Standard error of regression	0.016897			
Long run Variance	0.000644			
F-Statistics	57.73433			
Prob (*F*-Statistics)	0.000000			
RMSE	0.007995			

Table 5

Output of CCR: Response Variable $LnCO_2$

Variables	Coefficient	*SE*	*t*	*p*
LnFD	0.115908***	0.030132	3.846671	0.0006
LnREC	-1.525163***	0.226084	-6.746007	0.0000
LnTI	0.068903**	0.034202	2.014589	0.0498
C	6.082698	0.546716	11.12588	0.0000
R^2	0.985099			
Adjusted R^2	0.983502			
Standard error of regression	0.018914			
Variance (Long run)	0.000647			
F-Statistics	48.32568			
Prob (*F*-Statistics)	0.000000			
RMSE	0.010016			

Diagnostic Tests

The current study employed various diagnostic checks to establish the reliability and accuracy of the model. The diagnostic tests included the Jarque-Bera Test for normality of residuals, the Breusch-Godfrey LM Test for serial correlation, and the Breusch-Pagan-Godfrey Test for heteroscedasticity. The findings provided in Table 5 confirmed that there was no serial correlation and heteroscedasticity, and the residuals were also normally distributed. Furthermore, cumulative sum of recursive residual (CUSUM) test was also applied to verify the model's stability. Figure 2 showed the plot of CUSUM test, where blue line represented the values of residuals and red lines showed the confidence levels. Figure 2 confirmed that the model was stable over the specific period of time at 5% level of significance, as the values of the residuals were laying between the confidence levels.

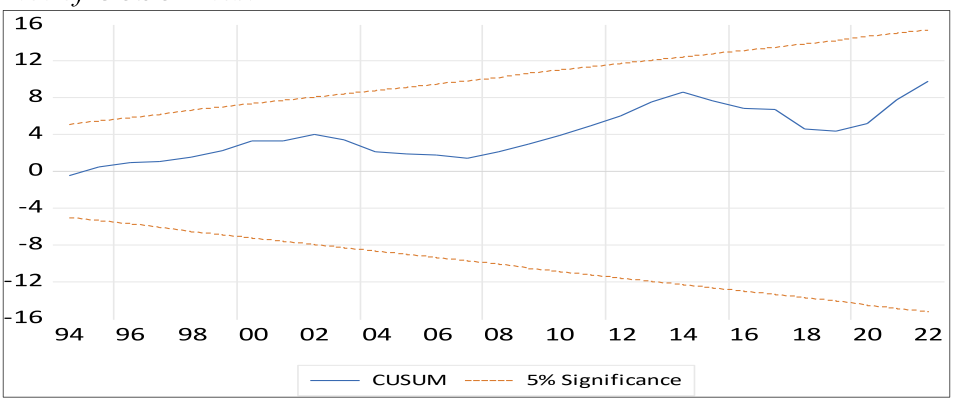
Table 6

Output of Diagnostic Tests

Tests	Statistic (p-Value)	Conclusion
Jarque-Bera Test	0.9360 (0.6252)	Indicated that the residuals had normal distribution
Breusch-Godfrey LM Test	1.6622 (0.2086)	It was concluded that serial correlation was not present
Breusch-Pagan-Godfrey Test	2.2623 (0.3646)	It was derived that the issue of heteroscedasticity was not present

Figure 2

Plot of CUSUM test



Conclusion

The current study explored the relationship between FD, REC, TI, and environmental sustainability in Pakistan. The data series was collected over the period of 1991-2024 from WDI and WIPO. The unit root tests of ADF, DF-GLS, and P-P were applied for determination of the order of integration in the study variables. The DOLS model was applied to look for the long run impact of FD, REC, and TI on CO_2 in Pakistan. The results indicated that FD and TI were positively related with CO_2 emission which degraded the environment in Pakistan. Conversely, REC helped achieve the sustainability in the environment in the long run. To check the robustness of the DOLS model, FMOLS and CCR models were applied.

The finding of TI was rather unexpected, suggesting that innovations might be focused on productivity in energy-intensive sectors rather than green technologies. This could be due to a dirty innovation bias, limitations in measuring patent quality, or lagged effects where environmental benefits might take time to materialize. It could be concluded that innovation in Pakistan might not be as eco-friendly as expected. Furthermore, the positive relationship of FD with CO_2 emission in Pakistan implied the expansion of industry, particularly in sectors, such as manufacturing and construction that relied heavily on fossil fuels. Similarly, improved financial access might boost household consumption of energy-intensive goods (e.g., vehicles, air conditioning) and raising CO_2 emissions in Pakistan. Therefore, financial institutions may support carbon-intensive energy and infrastructure projects due to the absence of green financial regulations in Pakistan.

Recommendations

- The government should encourage investments in green energy projects and development of a robust financial infrastructure that support environmental sustainability in the long run.
- The innovations in clean technologies and renewable energy may be promoted by offering grants and tax credits to public and private investors.
- The policymakers should design policies which mainstream the use of green energy in economic activities in place of fossil fuels to reduce CO_2 emissions and enhance stability in the environment.

- Environmentalists, as key stakeholders, should advocate for stricter environmental regulations, monitor policy compliance, and promote awareness campaigns to support sustainable practices.

Conflict of Interest

The author of the manuscript has no financial or non-financial conflict of interest in the subject matter or materials discussed in this manuscript.

Data Availability Statement

The data associated with this study will be provided by the corresponding author upon request.

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