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Research Article

IMPACT OF GREEN TECHNOLOGY AND INNOVATION ON C02 EMISSIONS IN PAKISTAN

Khuld Jamshaid[1], Prof. Dr. Abdul Ghafoor Awan[2]

1. Research Scholar, Department of Economics, University of Southern Punjab, Multan, Pakistan. khuldmajida12@gmail.com
2. Dean, Faculty of Social Sciences, University of Southern Punjab, Multan, Pakistan.
Corresponding author Email drabdulghafoorawan@gmail.com
OIRCID ID: https://orcid.org/ 0000-0001-5767-6229

Abstract

The primary objective of this study is to examine the relationship between green innovation, Renewable Energy Consumption, GDP, Financial development index with CO2 emissions using time series data from 1992 to 2022 sourced from World Development Indicators. C02 emissions were a dependent variable, while independent variables include green innovation, renewable energy consumption, GDP and Financial development. Correlation and ARDL models were employed to identify the behavior of variables during study period. The findings reveal that renewable energy consumption exerts a strong and statistically significant negative effect on CO_2 emissions. The magnitude of the coefficient suggests that an expansion in renewable energy use leads to a substantial reduction in carbon emissions. Innovation also shows a negative association with emissions, although the effect is only weakly significant, indicating that technological progress may contribute to environmental improvement when it is efficiency-driven or environmentally oriented. In contrast, economic growth displays a positive and statistically significant impact on CO_2 emissions, while financial development index shows a positive but statistically insignificant.

Key words: C02 emission; Renewable energy consumption; innovation, GDP, FDI.

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1.Introduction

1.1. Background of Study:

Carbon dioxide (CO_2) is a key driver of climate change and pose significant economic threats at both global and national levels. Globally, rising CO_2 emissions intensify climate-related shocks—such as extreme temperatures, floods, and droughts—which disrupt supply chains, reduce labor productivity, damage infrastructure, and ultimately lower long-term economic growth and global GDP (IPCC, 2023; World Bank, 2024).Latest empirical findings show that countries with high carbon intensity face increased macroeconomic instability, higher adaptation and mitigation costs, and declining investment efficiency, particularly in climate-sensitive sectors such as agriculture and manufacturing (OECD, 2023). In Pakistan, although its share in global CO_2 emissions is small, the economic consequences are disproportionately severe due to structural vulnerabilities, energy inefficiencies, and climate-sensitive livelihoods. Recent econometric evidence indicates that CO_2 emissions in Pakistan are closely linked with fossil fuel–based energy consumption, industrial expansion, and economic growth, which in turn exacerbate environmental degradation, reduce agricultural productivity, and increase public health expenditures, thereby constraining sustainable economic development (De Sherbinin et al., 2007; Iqbal et al., 2024). Consequently, the literature emphasizes that transitioning toward renewable energy, improving energy efficiency, and integrating climate policies into economic planning are crucial for reducing CO_2 emissions while safeguarding long-term economic stability in Pakistan and the global economy (IPCC, 2023; World Bank, 2024).

According to the World Bank (2019), the 10 most developed nations produce almost 62% of the global GDP because they consume 70% of the total energy resources and emit two-thirds of the total carbon in the world (Metz et al., 2007). The fast population leads to economic growth and technical improvements, which

in turn increases the need for energy in both advanced and developing countries. The balance between environment and economic growth can be created by technological advancements (Aronsson et al., 2010; Hübler et al., 2012). Better technological progress in the field of renewable energy and energy efficiency can promote sustainable development (Nordhaus 2007). Since renewable energy sources don't damage the environment, their use can slow down environmental degradation (Zhang et al., 2022). Thus, the usage of renewable energy can slow down environmental degradation because it doesn't spoil the environment (Khan et al., 2021d; Zafar et al., 2020; Zhang et al., 2022). International trade also plays a crucial role in environmental degradation because it provides developed nations to export their polluting industries to other countries (Liu et al., 2018),

Pakistan's economy, society, and ecosystem suffered greatly because of the 2010 and 2012 heavy floods, which also destroyed 20 million homes, besides causing many human deaths and injuries. The demand for energy is rising due to population growth, improving lifestyles, industrialization, and increased economic activities. Carbon dioxide accounts for 75% of greenhouse gas emissions and its main source is fossil fuels, which meet almost 85% of the world's energy demand. Climate change severely impacts Pakistan which contributes far less to global carbon emissions than other developing countries. The dirty industries are mostly responsible for emissions. Further, transport sector is rapidly expanding in Pakistan, leads to produce significant CO2 emissions. Heavy emissions are produced by outdated industrial processes and traditional production methods. Rice paddies and cattle farming are two examples of agricultural activities that produce methane emissions. The lack of recycling facilities and ineffective waste management contribute to the increase of greenhouse gas emissions. Addressing environmental issues and lowering carbon footprints require innovation and technology. Cleaner production methods, smart agriculture, electric and hybrid cars, renewable energy, energy efficiency, and waste management technology are the main areas of influence.

Pakistan has taken numerous initiatives such as National Development Council (NDCs), National Climate Change Policy, and Renewable Energy Policy to fulfill its international commitment to bring down CO2 emissions level at 1.5C'. Challenges in adopting new technologies include financial constraints and lack of infrastructure, but there are opportunities for international support, public-private partnerships, and domestic innovation. But the visible impact of these initiatives has yet to be seen. There is a need for deeper investigation into the impact of technological advancement and innovation on CO2 emissions in Pakistan.

1.2 Research Objectives:

The primary objectives of this research are given below:

1.To examine the impact of green innovation on carbon dioxide (C02) rlease in Pakistan.

2. To analyze the impact of renewable energy resources on C02 release in Pakistan.

3. To investigate the impact of GDP growth on CO2 release in Pakistan.

4. To study the link between financial development and CO2 release.

1.3 Research Question:

To explore the objectives, the current study intends to address the following research questions:

1.What is the impact of innovation on carbon dioxide (C02) release in Pakistan?

2.What is the relationship between renewable energy consumption and carbon Dioxide (C02) release?

3. What is the influence of GDP growth on CO2 release in Pakistan?

4. What is relationship between financial development and CO2 emissions in Pakistan?

1.4. Significance of Study

This research tends to fill existing gaps in the literature by providing a comprehensive analysis of the potential effect of innovation and technological

advancement on carbon release in Pakistan. By integrating diverse data sources and employing a mixed-methods approach, the research offers a nuanced and detailed understanding of the multifaceted interactions between technological advancements and emissions reduction. The study's cross-sectoral focus—covering energy, industry, residential, and transportation sectors— ensures a broad perspective on the overall impact of technological innovations. Furthermore, thorough analysis of regulatory systems and policy frameworks emphasizes how important good governance is for advancement of low-carbon technologies. The study offers useful insights that can assist in overcoming institutional, technological, and financial obstacles by identifying hurdles and suggesting actionable alternatives. This research also fills a gap in the literature by replicating itself in the Pakistani context only as this environment has a different set of social, economic, political and environmental dynamics.

The rest of the paper is organized as follows: section 2 discusses existing literature, identified research gaps and develop hypotheses.; section 3 explains research design, selected variables, model specification and analytical techniques. Section 4 elaborate empirical results and the paper conclude with discussion, practical implications, theoretical contributions, constraints and suggestions for further research.

2: Literature Review

2.1 Theoretical foundation

There are many mainstream theories which directly relate to this study. In this regard, first one is Theory of Green Innovation developed by René Kemp, Arthur P. J. Mol, and Martin Janicki. This theory predicts that development and use of green technologies significantly affect CO2 emissions. Later, extensive empirical research was conducted on this theory all over the world. For example, Acemoglu., Gancia & Zilibotti, 2015; Braun & Wield (1994) discovered that green technological innovation refers to producing green products to reduce environmental footprints,

raw materials, and energy consumption. Wang et al. (2021) argued that green technology innovation are a set of values aimed at energy maintenance, environment optimization and economic development. Technological change causes energy saving and emission reduction (Long et al., 2017; Sellitto et al., 2020). However, studies show that green tech is usually positive and reduces carbon footprint. That is why green technology is very important, and it is the only option to reduce emissions and simultaneously achieving economic growth. Simon Kuznets conceptualized his theory for income inequality, but Grossman and Krueger (1991) extended it to environmental degradation. Now this theory is known as Environmental Kuznets Curve hypothesis. This hypothesis assumes an inverse association between environmental and economic growth. This underlines in the Pakistani situation the need of accelerating the adoption of light-green technology to shift the turning point of the EKC curve. Another relevant theory is *The Diffusion of Innovation theory* conceived by Roger (1962). According to this theory, the adoption of green technologies depends on factors such as relative advantages, compatibility with existing systems, complexity, trialability, and observability. For Pakistan, the adoption of green innovations is influenced by economic incentives, societal awareness, and the availability of supportive infrastructure. Further, Porter (1991) hypothesis posits that well-designed environmental regulations can stimulate innovation and competitiveness, leading to economic benefits alongside environmental improvements. In the context of Pakistan, implementing regulations such as carbon pricing, emissions standards, and renewable energy targets could drive green innovation while reducing CO_2 emissions. This theory highlights the role of policy interventions in fostering an environment conducive to green technology development and adoption. Scholars like Schmoch 2007) presented Technology-push and Demand-Pull Theory. This theory emphasizes two main drivers of technological innovation: technology-push, where advancements arise from research and development (R&D) efforts, and

demand-pull, where market demand stimulates innovation. In Pakistan, both aspects are relevant. Public investment in R&D can accelerate the development of green technologies, while public awareness campaigns and subsidies can create market demand for renewable energy solutions and low-emission practices. Frank W. Geels and others (2002, 2004) offers Sustainability transition theory which focuses on the long-term structural changes required to achieve a low-carbon and sustainable economy. This framework emphasizes the interplay between technological innovation, societal norms, institutional arrangements, and policy frameworks. In Pakistan, transitioning to sustainability requires fostering collaboration among stakeholders, including government agencies, private enterprises, and civil society, to create systemic shifts toward green practices and low-emission technologies. The theoretical literature conceptualizes CO_2 emissions as a direct outcome of energy consumption patterns, technological progress, and economic expansion. Innovation, particularly green and energy-efficient technologies, is viewed as a key mechanism for reducing environmental degradation by enhancing energy efficiency and enabling the substitution of fossil fuels with renewable sources (Hanif et al., 2019; Yildirim et al., 2012; Long et al., 2015; Rehman et al., 2021). The Environmental Kuznets Curve (EKC) framework further theorizes a nonlinear link between economic growth and environmental deterioration, proposing that emissions initially increase with GDP uplift but reduce after a certain income threshold reached as economies adopt green technologies and stronger environmental rules (Dong et al., 2016; Adams & Nsiah, 2019).

2.2 Empirical review of literature.

2.2 Link between Growth, Finance, and Emissions

Theoretically, economic growth (GDP), financial development, and foreign capital inflows influence CO_2 emissions through scale, composition, and technique effects. While GDP growth expands production and energy demand, its environmental impact depends on the energy mix and the level of technological sophistication

(Banerjee, 2022). Financial development and FDI are theorized to play a dual role: they can either increase emissions by facilitating industrial expansion and energy consumption or reduce emissions by financing green technologies and renewable energy transitions (Tamazian et al., 2009). Consequently, theory emphasizes the importance of institutional quality, regulatory frameworks, and policy incentives in directing innovation and financial resources toward sustainable, low-carbon development paths.

2.3 Link between Renewable Energy, Innovation, and CO_2 Emissions

Empirical evidence supports the emissions-reducing role of renewable energy and green innovation. Studies find that renewable energy consumption, including solar, wind, hydropower, and renewable energy in agriculture, significantly lowers CO_2 emissions, whereas non-renewable energy use increases environmental degradation (Liu et al., 2017; Mensah et al., 2018; Inglesi-Lotz & Dogan). Bhattacharya et al. 2016; Saeed & Awan, 2020) further document that renewable energy use positively contributes to economic growth in developing economies, indicating the feasibility of decoupling growth from emissions. In Pakistan, empirical findings suggest that the adoption of green technologies and improvements in energy efficiency reduce carbon emissions, although their diffusion is constrained by financial limitations, technical challenges, and weak policy implementation (Rehman et al., 2021). Raza et al. (2020) pointed out that conservative technology like smart grid, efficient lighting including LED, and high energy efficient home appliance can reduce remarkable emissions and energy utilization. However, there are some barriers to implementation such as high upfront costs, lack of awareness by industries and consumers. Ahmad and Khan (2021) argue that emissions could be significantly reduced by introducing electric vehicles and improving public transport infrastructure. The government should provide incentives to promote electric vehicles, green infrastructure and green products.

2.4 Link between GDP, FDI, and CO2 emissions

Empirical studies reveal mixed results regarding the growth–emissions nexus. While economic expansion and financial development increase energy consumption in South Asian economies, they often intensify CO_2 emissions in the absence of clean energy transitions (Batool et al., 2022). Consumption-based emissions are found to be positively correlated with GDP and imports, whereas exports tend to reduce territory-based emissions (Awan, 2015;Hasanov et al., 2018; Dong et al. (2016) report no empirical support for the EKC hypothesis in the case of consumption-based emissions, instead identifying a linear and increasing relationship. However, recent evidence indicates that when financial development and FDI are aligned with green innovation and renewable energy investment, they contribute positively to carbon neutrality and green economic growth (Khan et al., 2022). Overall, empirical literature highlights that sustained emission reduction requires not only economic growth and capital inflows but also targeted innovation, renewable energy expansion, and strong institutional support.

2.5 Research gap

The strength of this paper is that it has assessed the impacts of innovation, technology and renewable energy consumption and GDP growth on carbon emission in Pakistan at the national level rather than the specific sector or organization. In contrast to other studies that rely on one source of data, the present study employs a multi-source data collection approach by using national databases, policies, and global literature, reduced variability and elimination of guess work in the results. It is unique in this perspective in addition to the fact that it employs a dual purpose quantitative and qualitative approach. Other quantitative methods include descriptive Statistics, ARDL approach, and Policies and their effect on carbon emissions. Moreover, compared to the previous studies which analyze the influence of technical improvement in separate sectors, this paper's cross-sectoral approach examines the effects of improvement in the sectors related to energy,

industry, residential, and transport and thus, provides a broader view on overall impact of innovation and technology.

3. Research Methodology

The main objective of this study is to examine the relationship between green innovation, Renewable Energy Consumption, GDP, Financial development index with CO_2 emissions. Patent applications are proxied for innovation while CO2 emissions was proxied for environmental quality. The study selected these variables, and their relevant data were taken from World Bank's World Development Indicators, which is a valid source and extensively used by renowned researchers spanning from 1992 to 2022. We used ARDL approach to estimate relationships between these variables. We used various diagnostic tests to check endogeneity issues, multicollinearity, serial correlation and heteroscadascity problems in the model. CO_2 emissions are measured in metric tons. We constructed an aggregate FD index using principal component analysis (PCA), a well-known analytical method. The formula for the FD Index is.

$$\sum n\ i=1\ wi \times FSI$$

where FSI is the element's value of each financial indicator, wi is the weight (the ratio of the variance clarified by each analyst to the variability explained by all additional indicators), and functional form of FD index is as follows:

$$wi = vi \sum n\ i=1\ vi \times 100$$

Based on the above variables we constructed an econometric model to estimate statistical relationships between variables. This model is expressed in the following equation.

$$CO2t = f\ (RECt, INOVt, GDPt, FDIt) \quad (1)$$

To process a log-linear structure rather than a linear configuration for the observed analysis, we transformed all the parameters into a natural log. The log-linear function of the model is as follows:

$$\text{Ln } CO2t = \alpha0 + \alpha1 \ln RECt + \alpha2 \ln INOVt + \alpha3 \ln FDt + \alpha4 \ln GDPt + ut \quad (2)$$

We are further simply the equation as:

$$CO2 = f(\beta1RECt + \beta2INNOVt + \beta3GDPt + \beta4FDit + \mu i) \quad (3)$$

We used different statistical techniques to estimate relationships between independent and dependent variables. For example, we employed ADF test is employed test stationarity in the time series. It is used to test the null hypothesis which assumes that there is no unit root in time series data and the variables are stationers at different levels. We used Correlation matrix which is an arithmetic tool to find out whether a relationship exists between pairs of variables and then determines their magnitude and effects. Correlation matrix is a valuable tool for discovering link between two variables. Further, The Bound test is used to identify long-term relationship between variables. It enables us to conduct further analysis. We applied ARDL (Autoregressive Distributed Lag) model to estimate long-term association between explanatory and explained variables. This model is used to observe both short-term and long-term relationships between study's variables particularly when the variables are stationary at 1(0). To check the robustness of the model we used different diagnostic tests to identify multicollinearity, serial correlation and heteroscedasticity issues in the model. A serial correlation makes the findings spurious, while multicollinearity shows correlations between independent variables and it makes it difficult to measure individual impact of these variables in dependent variables. Heteroskedasticity shows that the regression model lacks persistent variance. A scenario where the limited variance of Y changes with X is known as heteroscedasticity. We also used Ramsey Reset Test to identify misspecification of the model. Specifically, it tests whether adding nonlinear terms (powers or products) of the independent variables can significantly improve the model's fit. The idea is to detect if there is evidence that the model is missing important nonlinear relationships. We used Jacque Bera Test to ascertain if a residual is normally distributed. It tests whether statistics are consistent and

distributed asymptotically chi-square two degrees of independence when used to test the null hypothesis which assumes that the residuals are normally distributed.

33 Description of Variable:

3.3.1 CO2 Emission:

CO2 emissions are released in the atmosphere due to mostly human economic activities. This leads to carbon emissions. The sources of CO2 emissions include fossil fuels (coal, oil, and natural gas), manufacturing processes, deforestation, and specific agricultural farming. The Earth's atmosphere retains heat and experiences climate change due to the greenhouse gas effect, which is intensified and compounded by carbon emissions. Trends of CO2 emissions in Pakistan during 1996-2022 is exhibited in Figure 1.

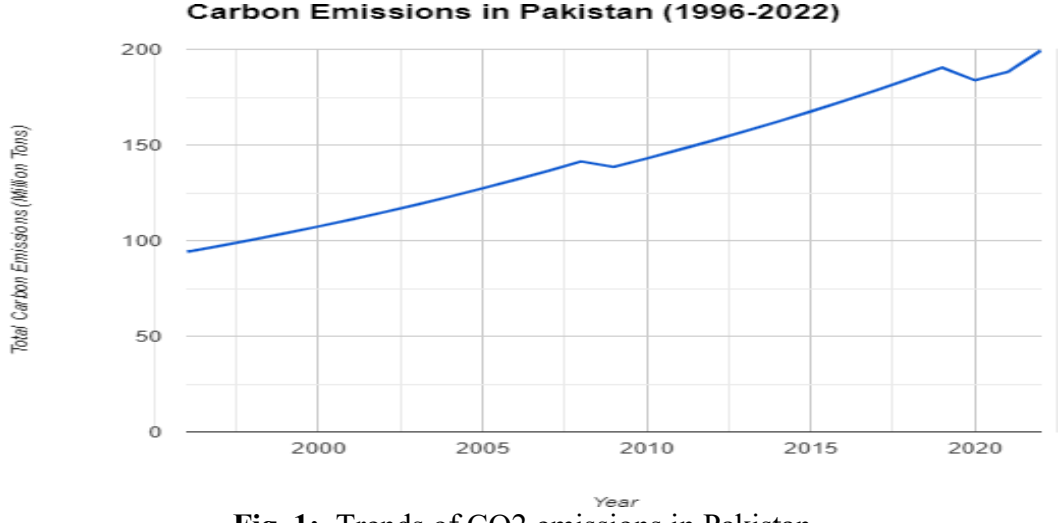


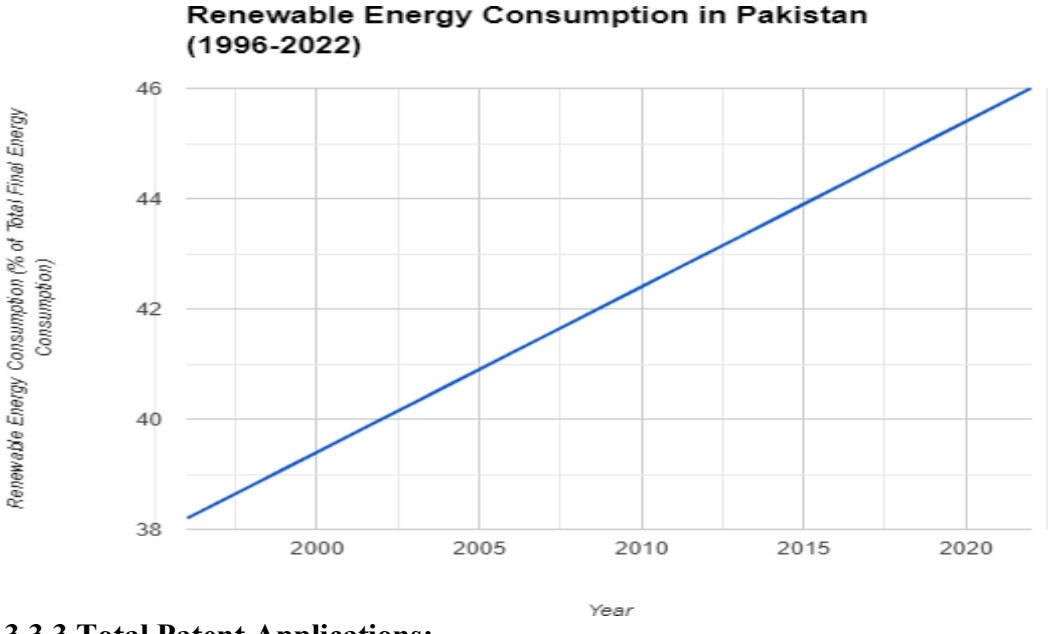
Fig. 1: Trends of CO2 emissions in Pakistan.

3.3.2 Renewable Energy Consumption:

Renewable resources are those which regenerate themselves naturally over a period and they do not deplete when we use them. Now the whole world is moving towards renewable energy to reduce reliance on fossil fuels which are the main cause of environmental degradation. Renewable energy consumption is rapidly rising in Pakistan due to adoption of Solar, wind and biomass technologies and their

share have reached around 50% in total mix-energy production. Trends of renewable energy consumption can be observed in Figure 2.

Fig 2: Trends of renewable energy consumption in Pakistan.



3.3.3 Total Patent Applications:

Innovations are measured in total number of applications registered with the relevant Government Department. This may be a new idea, a new product, a new process. Their total numbers reflect how many scientists and researchers are making innovations in a country and comparison of innovations is made among countries because of number of patent applications. If we see the historical trends, we found that the average patent applications from 1980 to 2021 is 115. The minimum applications were 16 in 1996 while the maximum of 426 patent applications was noted in 2021, showing rising trends over the years (The Global Economy, 2021). Figure 3 shows trends of patent applications from 1980 to 2021.

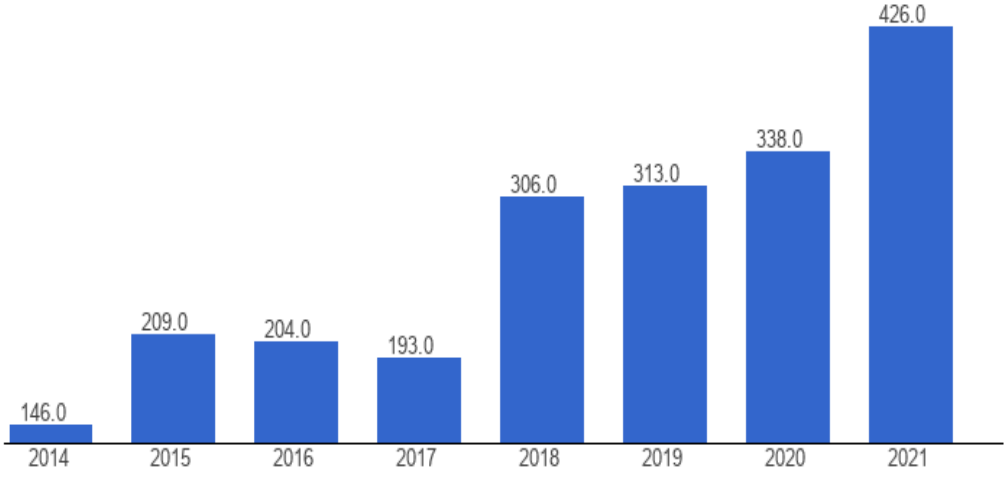


Fig 3:Trends of Patent applications in Pakistan.

Source: The Global Economy, 2021.

3.3.4 Economic Growth:

Gross Domestic Product (GDP) refers to the number of products and services produced during a specific period. It reflects productive capacity and wealth generation of a country. GDP growth is not smooth in Pakistan and wider fluctuations can be observed in it from Figure 4.

Fig 4: GDP growth over the period.

3.3.5 Financial Development Index

This index includes stock market indicators, money supply, and domestic credits as percentage of GDP. A well-structured financial system facilitates the development of financial activities in financial markets. The financial development in Pakistan during 1996-2022 is shown through FDI, which can be observed in Figure 5.

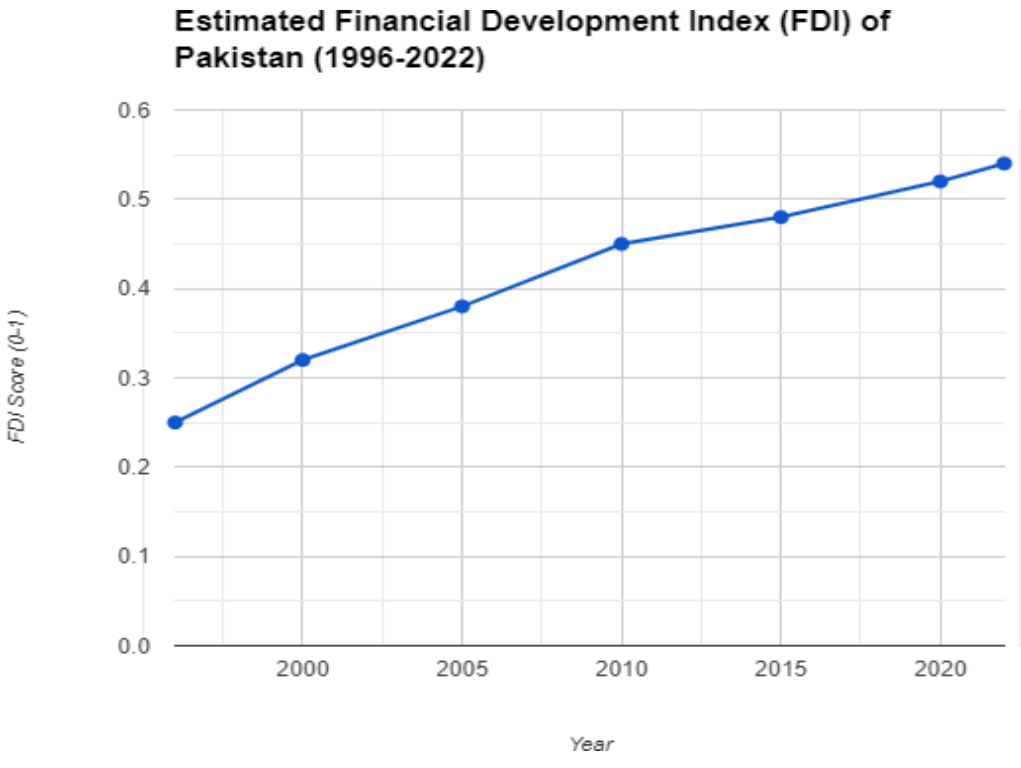


Fig 5: Trends of Financial development Index

4. Data Analysis

4.1 Descriptive statistics

The analysis of descriptive statistics is presented in Table 1.

Table 1:

Descriptive Analysis.

Variables	CO2 Emissions	REC	INOV	GDP	FDINDEX
Mean	-0.324217	3.867797	9.173062	7.158798	6.13E-16
Median	-0.325855	3.858622	9.428431	7.160548	0.238947
Maximum	-0.085043	3.954508	10.69311	7.436002	1.751070
Minimum	-0.478090	3.740048	4.444503	6.941077	-2.662624
Std. Dev.	0.109885	0.057897	1.343932	0.163725	1.257176
Skewness	0.221495	-0.253761	-1.734026	0.144860	-0.911438
Kurtosis	2.203428	2.410610	6.814226	1.787362	3.000716
Jarque-Bera	0.934612	0.680579	29.89767	1.748734	3.738236
Probability	0.626688	0.711564	0.000000	0.417126	0.154260
Sum	-8.753862	104.4305	247.6727	193.2876	1.99E-14
Sum Sq. Dev.	0.313944	0.087154	46.96001	0.696952	41.09278

Source: Author owns calculations using E-view software.

The results of the Descriptive Analysis show that Economic growth (GDP) ranges from 0.696 to 7.436, Renewable energy consumption (REC) ranges from 0.711 to 3.954, CO2 emissions (CO2) range from 0.1098 to 2.2034, and Total patent applications (INOV) range from -1.734 to 46.960. The entire variable's natural logarithm has been taken with the exemption of the FD index. Each of the variables

is regularly distributed, as shown by the skewness. Furthermore, the kurtosis suggests that all variables—except GDP—have a regularly distributed probability. Furthermore, only GDP conforms to normality, owing to the Jarque-Bera probability. While the range of REC is extremely large, equal to 93.29%, the mean level of REC during the study period is 18.83%, and its standard deviation has a comparable level. Overall, the findings show normal distribution of data, and it can be used for further analysis.

4.2 Correlation Matrix

Correlation matrix shows the estimates of correlation analysis.

Table 2.

Result of the Correlation Matrix.

Variables	LCO2 EMISSION	LREC	LINOV	LNGDP	FDINDEX
LCO2EMISSIO N	1				
LREC	0.9454	1			
LINOV	0.7286	0.6720	1		
LNGDP	0.85754	0.7064	0.8175	1	
FDINDEX	0.76065	0.6448	0.4451	0.74691	1

Source: Author own calculation using E-view software.

The correlation matrix reveals strong and positive linear link among CO_2 emissions, renewable energy consumption, innovation, economic growth, and financial development. CO_2 emissions (LCO2) show a very strong positive association with renewable energy consumption (LREC = 0.9454), suggesting that periods of higher energy use—despite the presence of renewables—are still closely associated with increased emissions, possibly due to significant role of fossil fuels in the overall energy mix. CO_2 emissions also exhibits a strong correlation with economic growth (LNGDP = 0.8575) and financial development (FDINDEX = 0.7607), indicating that growth-oriented and financially expanding economies tend to experience

higher emission levels, particularly in developing countries such as Pakistan.

Innovation (LINOV) is also positively correlated with CO_2 emissions (0.7286) and GDP (0.8175), implying that technological progress is currently more aligned with scale effects of production rather than green or emission-reducing innovations. Moreover, financial development is strongly associated with GDP (0.7469) but demonstrates a moderate association with innovation (0.4451), pinpointing that financial resources may not yet be efficiently channeled toward clean technologies. Overall, strong correlations suggest potential multicollinearity concerns but also highlight the interconnected nature of energy use, economic growth, financial development, and environmental quality, supporting the use of advanced econometric methods such as ARDL for long-run and short-run analysis. The Correlation Matrix estimates also exhibited in Figure 6.

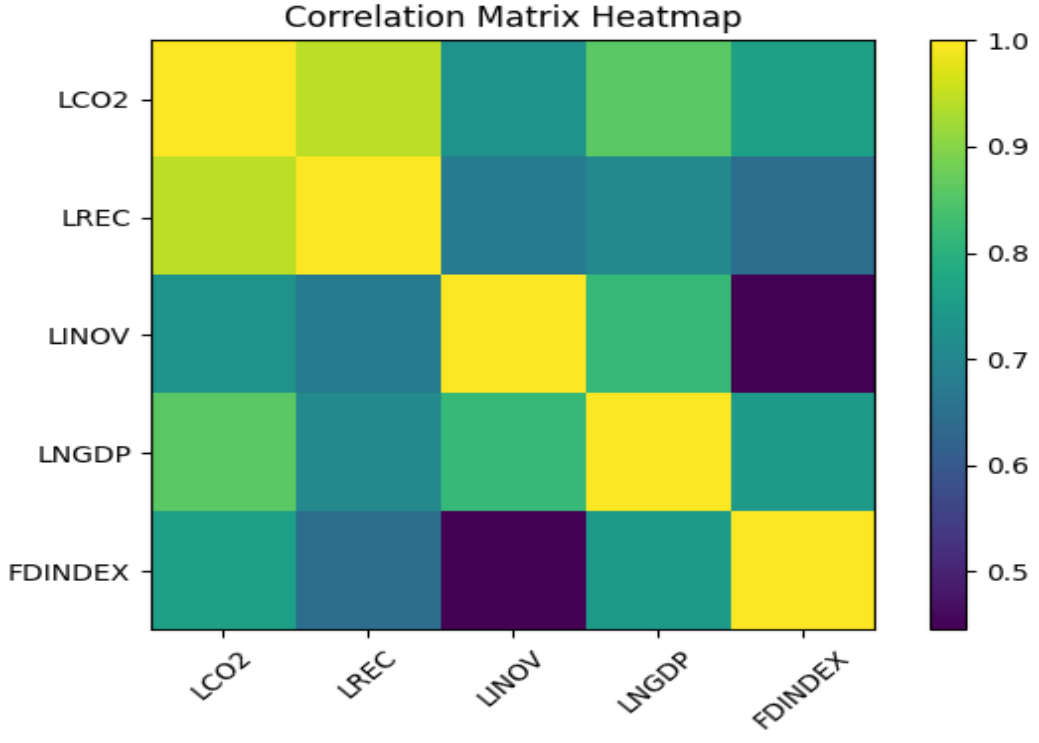


Fig 6: Correlation Matrix findings.

4.3 ADF and PP Tests

The estimates of ADF and Phillip Peront are exhibited in Table 3.

Table 3: ADF and Phillip Peron Unit Root outcomes

		ADF Results		Phillip Peron
Variables	Level	1st Difference	Level	1st Difference
CO2 Emission	0.0145	0.0104	0.6831	0.0290
REC	0.8055	0.0478	0.9408	0.0478
INOV	0.0820	0.0000	0.0000	0.0000
GDP	0.0176	0.0718	0.1949	0.0717
FDI	0.0001	0.0028	0.2209	0.0007

***, **, and * show significance levels at 1, 5, and 10%, individually.

Source: Author owns calculations using E-view software.

The results of ADF and PP tests reveal that all variables are cointegrated in different orders and as such we can use ARDL model for our emprical analysis.

4.4 Variance Inflation Factor (VIF):

This tool is used to identify multicollinearity among the explanatory variables. The estimates of VIF are presented in

Table 5:

VIVs findings.

	Coefficient	Uncentered	Centered
Variable	Variance	VIF	VIF
LREC	0.011863	11623.09	2.507392
LINOV	3.84E-05	215.7840	4.369882
LNGDP	0.003984	13376.40	6.734097
FDINDEX	3.32E-05	3.305930	3.305930
C	0.351568	23020.10	NA

Source: Author owns calculations

The results of VIF indicate no multicollinearity in the model and, therefore, we can apply ARDL model for further analysis.

4.5 ARDL Model

The estimated long-term estimates of ARDL Model are exhibited in Table 6.

Table 6.

ARDL Model Result:

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	-0.406436	0.949425	-0.428087	0.6751
LREC	-1.453270	0.136393	-10.65501	0.0000
D(LREC)	-1.453270	0.082773	-17.55725	0.0000
LINOV	-0.024866	0.014312	-1.737365	0.0977
D(LINOV)	0.059435	0.021375	2.780541	0.0147
LNGDP	0.350176	0.100149	3.496543	0.0023
D(LNGDP)	0.236250	0.127734	1.849552	0.0856
FDINDEX	0.004071	0.006854	0.594023	0.5592
CointEq (-1) *	-0.635921	0.099658	-6.381000	0.0000
R squared	0.959327	Mean dependent var		0.005656
Adjusted R-squared	0.948623	S.D. dependent var		0.050297
Durbin-Watson stat	2.642686			

*Dependent variable is CO2 emissions.

Source: Author own calculations using E-view software.

The ARDL model findings demonstrate a stable long-run association between CO_2 emissions and the selected independent variables, as evidenced by the negative and statistically significant error correction term. The coefficient of the lagged cointegration equation (–0.6359) confirms that deviations from the long-run equilibrium are corrected over time, with two-thirds of short-run disequilibrium

adjusting within a single period. This finding validates the presence of cointegration among CO_2 emissions, renewable energy consumption, innovation, economic growth, and financial development.

As far as long run findings of ARDL model, renewable energy consumption exerts a strong and statistically significant negative effect on CO_2 emissions. The magnitude of the coefficient effect suggests that an increase in renewable energy use leads to a substantial reduction in carbon emissions, reflecting its effectiveness in replacing carbon-intensive energy sources. Innovation also indicates a negative connectivity with emissions, although the effect is only weakly significant, indicating that technological progress may contribute to environmental quality when it is efficiency-enhancing or environmentally oriented. In contrast, economic growth displays a positive and statistically significant impact on CO_2 emissions, implying that higher levels of output and production continue to rely on emission-intensive processes. The coefficient of the financial development index is positive but statistically insignificant, suggesting that financial sector expansion, in the absence of targeted green financing, does not exert a meaningful influence on emission levels. The Short-run dynamics of ARDL model reveal similar but not identical patterns. Changes in renewable energy consumption significantly reduce CO_2 emissions in the short run, highlighting the immediate environmental benefits of clean energy adoption. However, short-run changes in innovation are associated with an increase in emissions, which may reflect transitional effects linked to industrial expansion, technology installation, or increased energy demand during the innovation phase. Short-term changes in economic growth also exhibit a positive effect on emissions, although the statistical significance is weaker, indicating that growth-related environmental pressures are present but less pronounced in the short run. Financial development remains insignificant in explaining short-term emission fluctuations. Overall, the model demonstrates strong explanatory power, with a high adjusted R-squared value indicating that the

included variables account for a large amont of the variation in CO_2 emissions. Durbin–Watson test suggests no evidence of serial correlation, supporting the robustness of the estimated results. Taken together, the findings indicate that renewable energy plays a decisive role in mitigating emissions, while economic growth and transitional innovation dynamics continue to exert upward pressure on environmental degradation. These results are demonstrated in Figure 7.

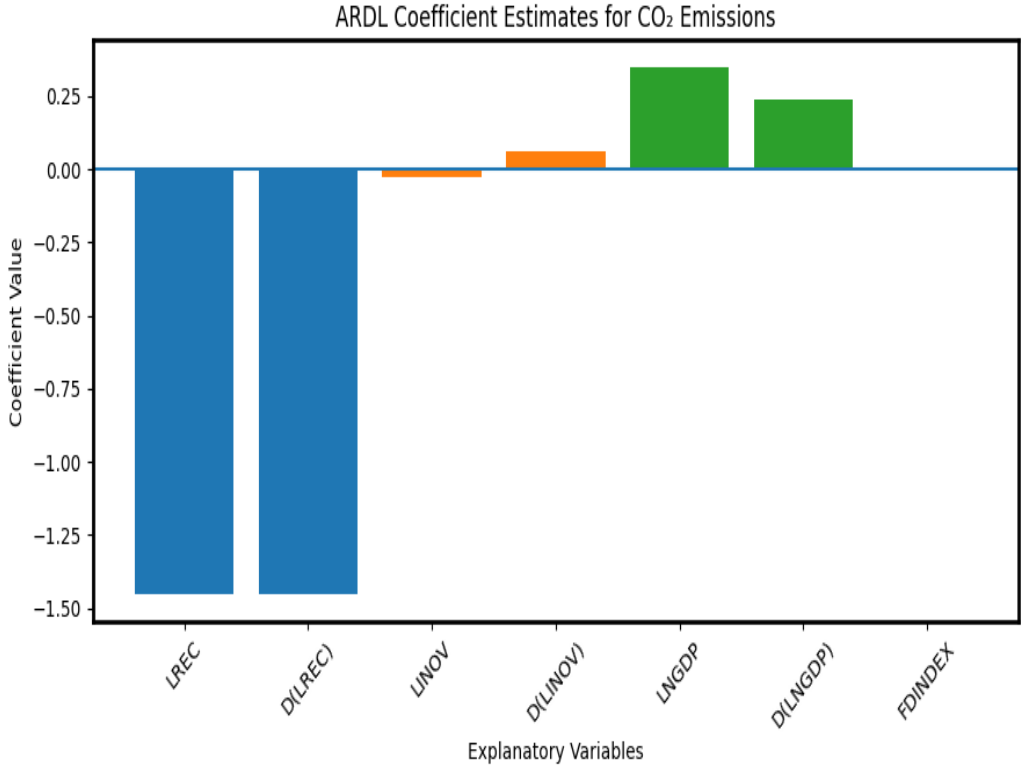


Fig 7: ARDL Model outcomes.

Figure 7 complements the econometric results and illustrates the contrasting effects of independent variables. The large negative coefficients for renewable energy in both the long and short-term visually confirm its dominant role in reducing emissions, whereas the positive coefficients of economic growth highlight its emission-intensive nature. The mixed signs associated with innovation further emphasize its differing short-run and long-run impacts on environmental quality.

4.7 Bound Test

Table 7 contains the outcomes of Bound Test.

Table 7

Bond Test Result:

ARDL Bound Test				
Test Statistic	Value	Signify.	I (0)	I (1)
F-statistic	5.000352	10%	2.2	3.09
		5%	2.56	3.49
		2.5%	2.88	3.87
		1%	3.29	4.37

Source: Author owns calculations

The Bound test developed by Pesaran et al. (2001) is used to detect long-term co-integration of variables. The assumption of no co-integration that F-statistics should be higher from upper and lesser bond critical values. The results show that all values are below F-statistics (5.000352) and, thus, long-run link among the variables has been confirmed. Hence, null hypothesis is rejected.

4.8 Diagnostic tests

These tests are employed to detect various issues in the study's model. The findings of these tests are presented in Table 8.

Table 8

Diagnostic Test:

Name of Diagnostic Testz	P-Value	Findings
Heteroscedasticity ((Breusch Pagan Godfrey)	0.5644	No Heteroscedasticity issue.
Heteroscedasticity (Harvey Test).	0.2676	No Heteroscedasticity issue

Serial Correlation: (Breusch Pagan)	0.1311	No Serial Correlation issue
Normality Test	0.494004	Normal Distribution of data

Source; Author owns calculations.

The model satisfies the three main assumptions of homoscedasticity, no serial correlation, and normally based on the outcomes of the diagnostic test were supplied. Both the Harvey and the Breusch-Pagan Godfrey tests for heteroscedasticity produced p-values larger than 0.05, which suggests that there is no conclusive evidence of heteroscedasticity. Furthermore, there was no discernible indication of serial correlation according to the finding of the Breusch-Pagan Serial Correlation test, indicating that there is no correlation between the residuals and independent variables. Lastly, the Jarque-Bera normality test estimates show that the data is normally distributed. Thus, it is proved that the model is well-specified and its findings are robust.

5. Discussion:

The objectives of this research were to examine relationships between innovation, renewable energy consumption. GDP growth and financial development with CO_2 emissions using time series data from 1996 to 2022 and employing ARDL approach to identify short-and-long term association between these variables. The study diagnosed that CO_2 release in Pakistan are significantly influenced by combination of factors, including past CO_2 emissions, Renewable energy consumption, GDP growth, and financial development. The financial development was measured through FDI. The empirical findings confirmed that there are both short- and-long-term links between these variables. The issue of CO_2 emissions is serious in Pakistan because of its dependence on fossil fuels, rising population and expanding urbanization, resulting in release of greenhouse gas emissions. Pakistan is promoting green technologies and renewable energy sources to reduce dependence on fossil fuels, but it involves heavy upfront costs due to which the transition from

non-renewable to renewable energy sources is slow. Pakistan must give green technology and innovation top priority to address these issues. Pakistan may decrease its carbon footprint and build a more resilient future by promoting electric vehicles, adopting sustainable farming practices, increasing energy efficiency, and using green energy technologies. However, it means that transition to the low-carbon economy will presuppose highly costly investments, changes in the current legislation, and further cooperation among the countries of the world. Through providing green innovation and technology, the nation may reduce the amount of its carbon emissions, advance defenses against the characteristics of climate change and improve wellbeing and sustainability of its people.

5.1 Policy Implications:

To obtain sustainability and minimize the level of CO2 emissions it is suggested that the government of Pakistan should provide tax incentives and subsidies for adoption of renewable energy sources to minimize dependence on fossil fuel energy. Policymakers should provide financial incentives for renewable energy sources adoption, like solar, wind, and hydropower to encourage enterprises and individuals to switch away from fossil fuels. Further, Government can promote public-private interaction for adoption of green technologies. Sufficient Funds should be allocated to R&D to encourage the local firms to innovate strategies to resolve Pakistan's environmental and economic issues. For this purpose, research centers and technical training programs should be launched to educate professionals on the development and maintenance of green technologies. There is also need to Strengthening Climate-Friendly Regulations Carbon Pricing and Emission Standards by introducing carbon trading schemes or taxes to provide an economic incentive for industries to reduce their emissions. Moreover, enforcement of Eco-Friendly Standards by formulating and enforcing regulations that require industries and businesses to adapt sustainable technologies. Pakistan should also integrate with Global Green Supply Chains Trade Policies for Green Technology by

providing easy access to state-of-the-art green technologies by lowering import tariffs for environmentally friendly machinery and components. There must be export facilitation for green products.

5.3 Limitations and ideas for future research:

Despite valuable contributions of this study, there are certain limitations regarding the availability of sector-specific and region-specific data, which in turn hinders in-depth analysis and the formulation of policies. This study ignored some important external factors, such as foreign trade dynamics, global green technology marketing, and geopolitics influencing the implementation challenges of domestic policy. Therefore, future work should focus on bridging the gaps mentioned above, including issues of data collection and analysis on energy use, CO_2 emissions, and dissemination of green technology into a single coherent dataset. This improvement in data collection methods may apply advanced analytical tools such as machine learning to determine trends and forecast accurately. Sectoral-focused studies ought to be commissioned to analyze the differential impact of green technological interventions in sectors like agriculture, industry, and services. In addition, there should be a more robust account of long-term longitudinal studies to address issues of sustainability.

5.3 Conclusion:

The results offer fresh evidence of detrimental effects of technology advancement and renewable energy consumption on CO2 emissions. Since new technologies have been developed employing renewable energy sources, the results highlight the implication of increasing their usage through innovation. Reducing energy use can benefit the environment, and modern machinery and technology can boost energy productivity. The application of renewable energy has been shown to lower carbon dioxide emissions and boost economic growth; nevertheless, the current level of renewable energy usage and technological advancements must continue to maintain the momentum. Pakistan could not resolve CO2 reduction-related issues alone

because of financial constraints and lack of the availability of technology. There is a need to seek global collaboration to obtain green finance to launch green projects for achieving long-term sustainability in the economy and society.

Data availability statement

The corresponding author will make available the data which supports the findings of this study on strong reasonable request**.**

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