Impact of Digital Ecosytem, Technological Innovations, Renewable Energy Consumption and Financial Development on CO_2 Emissions in Pakistan

Abdul Qayyum Khan[1] and Abdul Ghafoor Awan[2]

https://doi.org/10.62345/jads.2025.14.2.33

Abstract

This study examines the impact of the digital ecosystem, technological innovations, renewable energy consumption, and financial development on CO_2 emissions in Pakistan. As environmental sustainability becomes a global priority, understanding the role of digital transformation and technological advancements in mitigating carbon emissions is crucial. Using time-series data of 30 years (1994 to 2023) and applying econometric techniques like ARDL, the study explores how digitalization and technological progress influence environmental quality, while also assessing the contribution of renewable energy adoption and financial development in reducing emissions. The findings reveal that a digital ecosystem enhances CO_2 emission in Pakistan due to enhanced energy consumption and production through traditional energy sources. Surprisingly technological innovations also have negative impact on CO_2 emission. In developed countries like Pakistan, technological innovations have positive impact on environment. The possible reason for this negative relation is low investment in R&D and green technologies. Additionally, increased renewable energy consumption significantly reduces environmental degradation. However, the relationship between financial development and emissions is complex, indicating that financial expansion must be aligned with green investment policies. The study highlights policy implications for fostering a sustainable economy through digitalization, clean energy transition, and green financing.

Keywords: Digital Ecosystem, Technological Innovations, Renewable Energy Consumption, Financial Development.

Introduction

Climate change is widely recognized as one of the most critical global challenges of the 21st century, with greenhouse gas emissions—especially carbon dioxide (CO_2)—at the core of the issue. According to the Intergovernmental Panel on Climate Change (IPCC, 2023), CO_2 accounts for over 75% of total emissions. Reducing these emissions without hampering economic growth is a dilemma that almost all nations globally, particularly developing countries like Pakistan, must navigate. This study examines the complex relationship between CO_2 emissions and four critical variables such as emerging digital ecosystem, technological progress, adoption of renewable energy, and financial development. Despite shares of 1% of global greenhouse gas emissions, Pakistan is consistently ranked among the world's ten most climate-vulnerable countries. Repeated natural disasters—floods, droughts, extreme weather, and rapid glacial melt—severely threaten the country's food security, public health

[1]*Research Scholar, Department of Economics, University of Southern Punjab, Multan, Pakistan.*
Email: qayyumkhan588@gmail.com
[2]*Dean and Professor, Faculty of Social Sciences, University of Southern Punjab, Multan, Pakistan.*
Email: drabdulghafoorawan@gmail.com OICD ID: https://orcid.org/0000-0001-5767-6229

Compliance with ethical standards: There are no conflicts of interest (financial or non-financial). This study did not receive any funding.

infrastructure, and economic infrastructure. These issues are intensified by underlying national challenges, including widespread energy poverty, technological deficits, and persistent economic instability.

Pakistan's path of industrialization and rapid urbanization has significantly raised CO_2 emissions. Its energy sector, dominated by fossil fuels such as coal and oil, stands as the primary source. This situation underscores the urgent necessity for evolving a sustainable development model that integrates environmental protection, social equity, and economic growth. Under the 2015 Paris Agreement 195 countries agreed to cap global temperature while nations including the UK, France, Norway, and New Zealand have also pledged to achieve net-zero emissions by 2050.

Digitalization and technological advancement are increasingly recognized as pivotal instruments for climate action at global level. Digital ecosystems—networks integrating information and communication technologies (ICTs) into socio-economic growth model—provides potential sustainability gains through smart infrastructure improvement, real-time ecological monitoring, remote work capabilities, and efficient resource allocation. However, these systems simultaneously involve environmental costs, notably heightened energy demand and escalating electronic waste.

Technological innovation is a key factor for effective emissions reduction. Globally, growth in sustainable agricultural techniques, energize transportation, energy-efficient systems, and carbon curbing technology contributes to reduce CO_2 outputs. In Pakistan, however, the adoption of green technologies faces significant barriers: constrained financing, weak infrastructure, and insufficient institutional backing. Despite rising interest from both governmental and private sectors, more robust financial system and policy frameworks are essential. This research examines the contribution of both domestically generated and internationally transferred technological innovation to emission reduction in Pakistan and scrutinizes the adequacy of existing institutional frameworks to enable such shifts.

Renewable energy integration represents another crucial pathway for decarbonization. Pakistan is endowed with substantial renewable resources, particularly solar and wind potential. Recent governmental initiatives aim to elevate the proportion of renewables within the overall energy portfolio. Nevertheless, progress is hindered by governance shortcomings, fiscal limitations, and structural inefficiencies within the energy sector. Consequently, the shift away from fossil fuels toward cleaner energy sources proceeds slowly. This study investigates the impact of renewable energy utilization on CO_2 emissions in Pakistan, with specific focus on current adoption levels, the effectiveness of policy execution, and obstacles to wider implementation.

Financial sector development is equally vital for enabling the transition toward environmental sustainability. A well-functioning financial system can catalyze green investments by managing associated risks and improving capital accessibility. Instruments such as specialized green loans, environmental risk evaluations, and sustainability-linked incentives can encourage eco-friendly business operations. Although Pakistan's financial sector has expanded considerably, dedicated green finance mechanisms remain underdeveloped. This analysis probes whether the country's financial evolution is perpetuating environmentally damaging activities or facilitating a move toward a low-carbon economy. Hence, primary research questions of this study are as follows:

- How does Pakistan's evolving digital ecosystem impact CO_2 emissions—does it serve as a mitigating factor or pose new environmental risks?
- What is the role of technological innovation—both domestic and foreign—in reducing CO_2 emissions in Pakistan?
- How effective is Pakistan's renewable energy adoption in mitigating CO_2 emissions?

- Does financial development in Pakistan support high-emission activities or foster a transition toward environmental sustainability?
- To explore the above research questions this study aims at:
- To assess the impact of digital transformation on CO_2 emissions in Pakistan.
- To examine the influence of technological advancements and innovation on environmental sustainability.
- To evaluate the relationship between renewable energy usage and emission reduction in Pakistan.
- To investigate the role of financial development in promoting or hindering sustainable, low-carbon economic activities.

Literature Review

Digital Ecosystem and Environmental Quality

A number of studies assess the impact of the digital ecosystem on environmental quality. For example, Raihn (2023) used ARDL on Malaysian data, revealing an increase in internet use initially raises emissions, but reduces them over time, indicating a dynamic effect. Nguyen et al. (2020) and Raheem et al. (2020) observed a negative relationship between digital ecosystem development and CO_2 emissions in G-7 countries. Lu (2018) and Park et al. (2018) gave contrasting results—Lu found a positive environmental impact of digitalization in Asia, while Park noted long-run ecological deterioration in European nations. Sinha et al. (2022) highlighted Pakistan's digital progress and its dual role: potential for efficiency and risks like e-waste. Klimova et al. (2016) emphasized the centrality of digital infrastructure in modern economies. Avom et al. (2020) and Moyer and Hughes (2012) provided conflicting views about the economic and environmental value of digitalization. The review of above studies highlighted the fact that the findings are inconclusive and context-dependent, with studies differing by region (G-7, Asia, Pakistan, Europe) and methodology (linear vs nonlinear ARDL). Many studies do not jointly examine digital ecosystems with other critical variables such as renewable energy use or financial development. Therefore, we hypothesize:

H1: Digital Ecosystem positively correlates with environmental quality in development countries.

Technological Innovation and Environmental Quality

Studies by Ullah et al. (2023), Ali et al. (2023), Chen et al. (2023), and Ahmad et al. (2023) demonstrated that technological innovation can have mixed short-run and long-run effects, often reducing CO_2 over time. However, Chen and Lei (2018) and Khattak et al. (2020) reported that innovation may increase emissions, especially in industrialized or developing economies relying heavily on fossil fuels. Fernandez et al. (2018) and Paramati et al. (2021) support the positive impact of innovation in developed nations. This analysis confirms that the impact of technological innovation appears to be nonlinear and contingent on the energy mix, regulatory frameworks, and regional development status. Few studies consider interaction effects (e.g., innovation + renewable energy or innovation + financial development). Hence, we hypothesize:

H2: Technological innovation positively correlates with environmental quality in developing countries.

Renewable Energy Consumption and Environmental Quality

Multiple studies (Sadiqa et al., 2022; Zafar et al., 2019; Wang et al., 2023) have established a strong inverse relationship between renewable energy consumption and CO_2 emissions.

Islam et al. (2023) and Akram et al. (2020) provided case studies on Pakistan's solar and wind potential, citing barriers like infrastructure, investment, and policy fragmentation.
Studies across regions (MENA, E-7, Latin America, OECD) support similar conclusions.
This domain is well-established with consistent evidence supporting renewable energy's beneficial effects. However, contextual challenges in Pakistan (e.g., infrastructure, policy) merit more focused empirical inquiry. Thus, we can hypothesize:
H3: Renewable Energy consumption positively correlates with Environmental quality in developing countries.

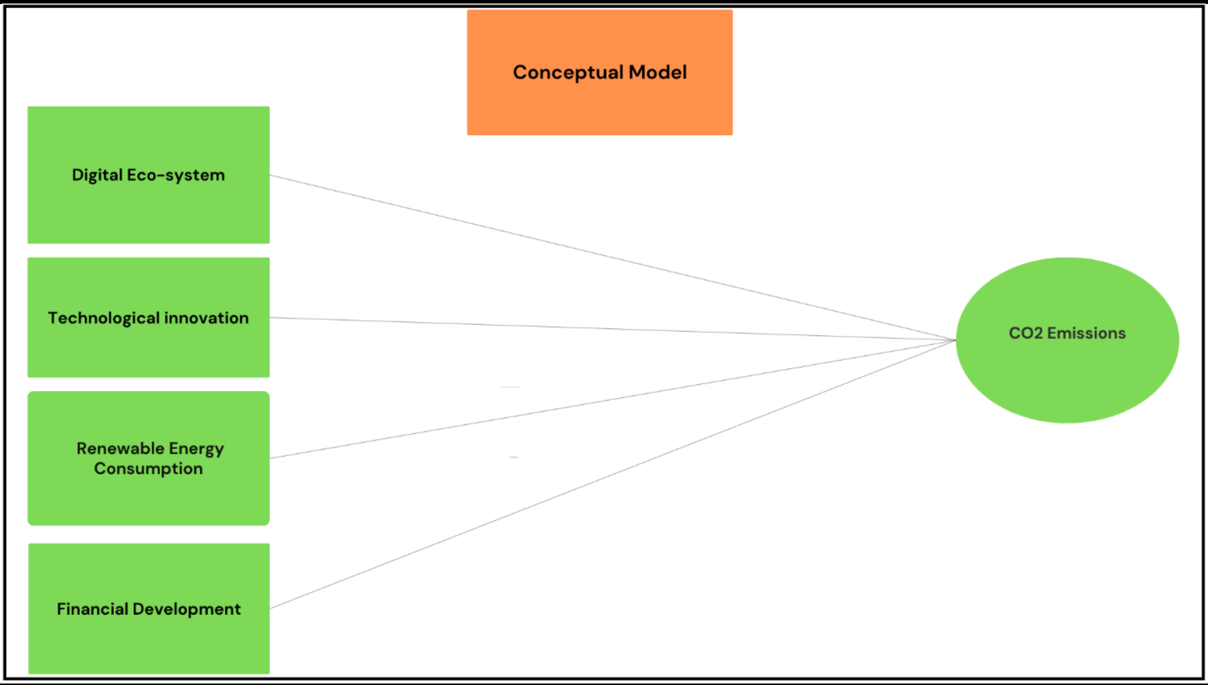
Financial Development and Emissions

The role of financial development (FD) in environmental outcomes is highly contested:
Jalil and Feridun (2011), Shahbaz et al. (2013) found positive impacts (FD reduces emissions) in Asia. Usman et al. (2022) and Ahmad et al. (2022) emphasized that FD can either mitigate or worsen environmental degradation depending on how the credit is utilized (green vs dirty sectors). This discussion proves that there's no consensus on whether FD is environmentally friendly. The lack of distinction between green vs brown financing or financial inclusion vs speculative capital flows weakens the conclusions. In short, we can hypothesize:
H4: Financial development positively correlates with environmental quality in developing countries.

Conceptual Model

The conceptual model constructed on the basis of objectives and hypotheses of this study is presented in Figure 1.

Figure 1: Research Model



Methodology

In this study we have focused our attention in examining the role of Digital ecosystem, Technological innovations, Renewable Energy Consumption and Financial Development in Pakistan. Time series data has been used, All the data which has been used in this study taken from World Development Indicators. (WDI, World Bank). The period of study is 30 years from 1994-2023. We have used index of No of internet users, number of broadband subscribers, No of landline users, number of cellular subscribers for digital ecosystem, number of patent submitted per year as technological innovations, renewable energy as energy produced by Wind, Solar and Hydro system and is used as % of total final energy consumption Domestic credit to private sector by Banks as Financial Development.

Specification of Model

CO_2=f (DES, TI, REC, FD)………………………………………………………… (1)

The above Economic model shows that CO_2 is the dependent variable and Digital ecosystem, Technological innovations, Renewable energy consumption and financial development are independent variables. This model is transformed into mathematical equation.

$C_{O2\ t} = \beta_1 + \beta_2 DES_t + \beta_3 TI_t + \beta_3 REC_t + \beta_3 FD_t + \mu_t$…………………………………..... (2)

An autoregressive distributed lag (ARDL) model is an econometric model. ARDL model was developed by Pesaran et al (1999) it analyzes the association amongst time series variables over the short and long term. This model is usually used while using variables with different levels of I(o) and I (1) or a combination of the two

ARDL cointegration method is the best when we analyze variables that are combined in different order, I (0), I (1) or a combination of both, and is strong when there is a single long-run association between the primary variables in a small sample size. Therefore, we applied ARDL model in our research.

$\Delta \mathrm{C02PCt} = \varphi + \varphi_1 \mathrm{DES}_{t-1} + \varphi_2 \mathrm{TI}_{t-1} + \varphi_3 \mathrm{REC}_{t-1} + \varphi_4 \mathrm{FD}_{t-1} + \sum_{i=1}^{q} \beta_1\, \Delta DES_{t-i} + \sum_{i=1}^{q} \beta_2\, \Delta TI_{t-i} + \sum_{i=1}^{q} \beta_3\, \Delta REC_{t-i} + \sum_{i=1}^{q} \beta_4\, \Delta FD_{t-i} + \varepsilon t$ … … … … … … … … …. (3)

In the given equation, Δ represents the initial difference. DES is digital ecosystem, TI is technological innovations, REC is renewable energy consumption, and t-1 is the appropriate lag selection using the Akaike information principles. The Φ and β will be approximated to determine the long-term association among the variables.

Error Correction Model

Error correction model is a powerful econometric tool used to identify the relationship between variables. This model is important because it captures both short-run dynamics and long-term equilibrium adjustments among model variables.

$\Delta \mathrm{C02PGt} = a + \sum_{i=1}^{q} \lambda_1 \Delta \mathrm{DES}_{t-1} + \sum_{i=1}^{q} \lambda_2 \Delta \mathrm{TI}_{t-1} + \sum_{i=1}^{q} \lambda_3 \Delta \mathrm{REC}_{t-1} + \sum_{i=1}^{q} \lambda_4 \Delta\, \mathrm{FD}_{t-1} + \sum_{i=1}^{q} + \omega\, ECM_{t-1}$…………………………………………………..(4)

The parameters in the above-mentioned short-run equation with the sign of summation (Σ) represents the short-run parameters, whereas the coefficient of ECM (ω) represents the time it takes to adjust to long-run equilibrium.

Results

Table 1: Descriptive Statistics

Statistic	LCO_2	DES	LTI	LREC	LFD
Mean	-0.318	1.15E-15	4.669	3.855	2.901
Median	-0.331	-0.268	4.713	3.854	2.812
Maximum	-0.085	3.267	6.144	3.992	3.237
Minimum	-0.527	-1.976	2.772	3.712	2.475
Std. Dev.	0.129	1.752	0.926	0.079	0.227
Skewness	0.153	0.448	-0.208	-0.173	0.119
Kurtosis	1.805	1.812	2.188	2.061	1.642
Jarque-Bera	1.903	2.769	1.040	1.250	2.374
Probability	0.386	0.250	0.594	0.535	0.305
Observations	30	30	30	30	30

In Table 1, mean values represent the average of each variable: LCO_2 (-0.318), DES (1.15E-15), LTI (4.669), LREC (3.855), and LFD (2.901). These central values offer a baseline understanding of the typical magnitudes within each series. Median values, representing the central tendency, are as follows: LCO_2 (-0.331), DES (-0.268), LTI (4.713), LREC (3.854), and LFD (2.812). The proximity of the median to the mean in most cases suggests relatively symmetrical distributions. Maximum and minimum values indicate the range of variation across the sample. For example, DES ranges from -1.976 to 3.267, showing substantial fluctuation, while LREC is more stable, ranging from 3.712 to 3.992. Standard deviation (Std. Dev.) reflects the dispersion around the mean. DES exhibits the highest variability (1.752), while LREC shows the lowest (0.079), suggesting that digital ecosystem variables are more volatile than renewable energy consumption. Skewness quantifies the asymmetry of the distribution:

- LCO_2 (0.153), DES (0.448), and LFD (0.119) are positively skewed, indicating a longer right tail.
- LTI (-0.208) and LREC (-0.173) are negatively skewed, implying a longer left tail.
- All skewness values fall within the range of ±1, suggesting mild asymmetry.

Kurtosis measures the "tailedness" of the distributions. A normal distribution has a kurtosis of 3 (mesokurtic). All variables have kurtosis values below 3, indicating a platykurtic distribution, which is flatter than the normal distribution and has lighter tails. Jarque-Bera statistics test the null hypothesis that the data are normally distributed. All variables have p-values greater than 0.05: This indicates that we cannot reject the null hypothesis, confirming that all the series follow a normal distribution at the 5% significance level. In short, , the descriptive statistics suggest that the data series are normally distributed with relatively low skewness and moderate dispersion.

Correlation Matric

Correlation Matrix describes whether the association between two variables is strong or weak and relation is positive or negative. The direction of the relationship can be positive or negative. There are three types of relationships, positive correlation, negative correlation, and zero correlation. If there is positive correlation both variables move or change in the same direction. In a negative correlation, both of the variables move in opposite directions. Here we see the relationship of the variables in table 2

Table 2: Correlation analysis

	LCO_2	DES	LTI	LREC	LFD
LCO_2	1				
DES	0.895	1			
LTI	0.907	0.881	1		
LREC	-0.976	-0.889	-0.923	1	
LFD	-0.579	-0.713	-0.690	0.614	1

Table 2 shows that there is a strong and positive correlation between digital ecosystem and CO_2 emission. If we use more devices and establish more infrastructure which is used to operate digital devices then there will be huge quantity of carbon emission. Technological innovations have even stronger effect on emission of CO_2. Consumption of renewable energy and CO_2 have strong negative correlation. If we utilize more renewable energy resources then there will be a huge decrease in CO_2 emission and vice versa. Financial development and CO_2 have also strong negative correlation. More is the financial development the lesser will be the carbon emission.

Unit Root Test

This test is used to diagnose whether the time series data is non-stationary and includes the unit root. The unit root specifies that the variables are exaggerated by extreme events and then return to baseline over time, suggesting no long-term trend or stability. Stationary time series data sets are essential for accurate estimation and forecasting in statistical analysis. We used the unit root test to assess whether statistical parameters such as mean and variance remained constant over time. If the assumption is non-stationary (includes unit roots), it can lead to false positive regression results and unreliable predictions. This is because statistics of non-stationarity change over time. In our analysis we used the Augmented Ducky-fuller (ADF) and Phillips Perron (PP) methods to know whether the time series data is stationary or not. Here are the results of the tests we applied, below in Table 3

Table 3: Unit Root Tests

	Augmented Ducky-fuller (ADF)		Phillips Perron (PP)	
Variable	**Level**	**First Difference**	**Level**	**First Difference**
CO_2	0.738	0.0006	0.724	0.0005
DES	0.999	0.003	0.998	0.003
TI	0.857	0.000	0.965	0.000
REC	0.777	0.0002	0.875	0.000
FD	0.633	0.004	0.768	0.004

In the above table 3 P-value of all the variables, estimated by both of the methods Augmented Ducky-fuller (ADF) and Phillips Perron (PP) used in our research is significant. Which shows that our data is stationary and there is no unit root in our data.

Bond Test

In ARDL techniques, bond test is applied to know the long-term association amongst the variables. If the value of F-Statistics is greater than the value of upper bond and the value of lower bond, it specifies that there exists the long run association amongst the variables and we can analyze data to determine the relationship and their impact.

Table 4: Bond Tet

			I(0)	I(1)
F-statistic	10.196	10%	2.68	3.53
		5%	3.05	3.97
		2.5%	3.4	4.36
		1%	3.81	4.92

In table 4 value of F-statistics is 10.196 and value of lower bond I (0) is 3.81 at 1% significant level and value of upper bond I(I) is 4.92 at 1% significant level which shows that long run relationship exists at even 1% significant level, although long run relationship also exists at 2.5%, 5% and 10% significant level

ARDL Model Results

The Autoregressive Distributed Lag (ARDL) model is extensively employed in time series analysis to estimate long-run relationships between variables. In this study, we utilized the ARDL approach to examine the long-run impact of digital ecosystem (DES), renewable energy consumption (REC), technological innovation (TI), and financial development (FD) on CO_2 emissions in Pakistan. CO2 emissions is proxied for environmental quality. The long-run results of ARDL model are reported in Table 5.

Table 5: ARDL Long-Run Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
DES	0.0402	0.0131	3.072	0.005
LREC	-0.2622	0.0532	-4.929	0.000
LTI	0.0597	0.0222	2.691	0.0127
LFD	0.1454	0.0612	2.375	0.0258

Note: CO_2 Emission is dependent variable.

The estimated long run results of ARDL model is given below:

$EC = LCO_2 - (0.0402 * DES - 0.2622 * LREC + 0.0597 * LTI + 0.1454 * LFD)$

The outcomes in Table 5 indicated that the coefficient of DES is 0.0402 and is statistically significant ($p = 0.005$), indicating that a 1% increase in the digital ecosystem index leads to approximately a 4.02% increase in CO_2 emissions. This positive correlation indicates that expanding digital infrastructure and technology adoption may escalate energy consumption, consequently elevating carbon emissions. These findings align with established research: Raheem et al. (2020) observed similar digitalization-driven energy demand intensification in G-7 nations, Cheng et al. (2019) documented parallel effects across Chinese cities, and Briglauer et al. (2023) confirmed this pattern in Kenya. Murillo et al. (2016) further contextualized the scale, noting that mobile networks and digital devices consume energy comparable to major industrial facilities—predominantly fossil-fuel powered. Supporting this, Lu (2018) and Avom et al. (2023) identified robust linkages between ICT proliferation and heightened CO_2 emissions. Conversely, the renewable energy consumption (REC) coefficient of -0.2622 proves statistically significant (*p* = 0.000), signifying that a 1% increase in REC correlates with a 26.22% reduction in CO_2 emissions. This inverse relationship validates clean energy's environmental advantages and resonates with conclusions by Charfeddine and Kahia (2019), Mukhtarov et al. (2024), Wang et al. (2023), and Baek (2016). These scholars attribute emissions reduction to renewables' sustainable, non-polluting characteristics. Mohsin et al. (2021) and Javed and Rapposelli (2024) extended this analysis, emphasizing renewables' critical role in advancing public health and achieving Sustainable Development Goals (SDGs), particularly environmental sustainability and energy security.

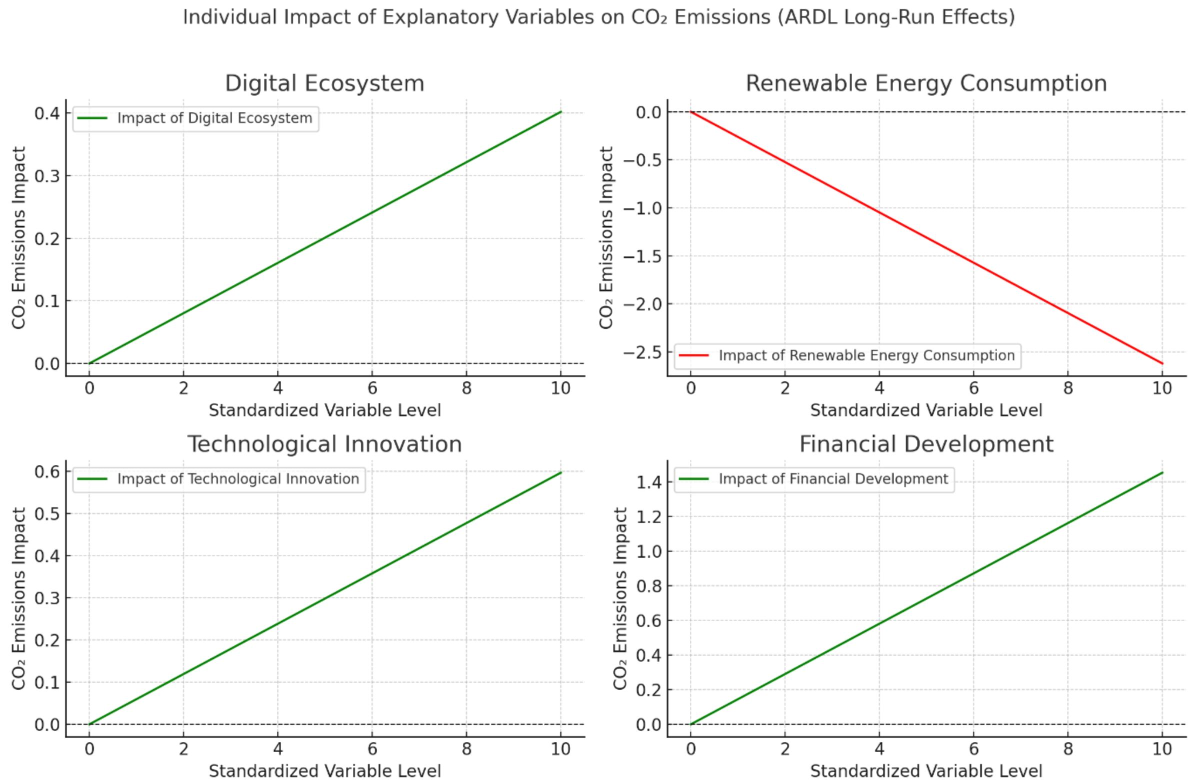
The technological innovation coefficient (0.0597; *p* = 0.0127) reveals a statistically significant positive association, implying 5.97% emissions increase per 1% innovation growth. This supports the rebound effect (Jevons paradox), wherein efficiency gains from new technologies stimulate higher production and energy use, negating potential ecological benefits. Such outcomes corroborate Saidi et al. (2020), Khan et al. (2020), and Yang et al. (2021), who observed that technological progress—while essential—does not guarantee immediate environmental improvements and depends heavily on deployment strategies. Environmentally calibrated innovations remain imperative for long-term emissions mitigation.

Financial development exhibits a coefficient of 0.1454, significant at the 5% level (*p* = 0.0258), indicating 14.54% emissions rise per 1% financial expansion. This suggests that while financial growth stimulates economic activity, it may simultaneously elevate energy consumption and environmental degradation when detached from sustainable investments. These results reinforce Ozturk and Acaravci (2013), Bashir et al. (2019), and Haini (2021), who linked financial sector growth to emissions-intensive industrial activity. Aljadani (2022) and Adebayo et al. (2021) further cautioned that without strategic green investment, financial development risks exacerbating ecological harm. Long-Term Implications of ARDL Analysis indicates that the digital ecosystem, technological innovation, and financial development demonstrate statistically significant positive impacts on CO_2 emissions. Renewable energy consumption, conversely, significantly reduces emissions—underscoring its critical sustainability role. These findings necessitate:

- Green financing mechanisms to redirect capital toward sustainable projects
- Low-emission technology innovation policies to counter rebound effects
- Renewable energy infrastructure expansion to capitalize on proven emissions reduction
- Environmental regulations for digital infrastructure development to mitigate energy footprints.

The ARDL long-term results are presented in Figure 2.

Figure 2: Prediction of negative and positive impact



Error Correction Model

Table 6: Short run analysis of ECM

Variable	Coefficient	Std. Error	t-Statistic	Prob.
DES	0.014	0.008	1.756	0.092
LTI	0.021	0.011	1.862	0.0754
REC	-0.022	0.004175	-5.392	0.000
LFD	0.065	0.031	2.040	0.052
C	4.431	0.534	8.296	0.000
CointEq(-1)*	-0.743	0.089	-8.269	0.000

The Error Correction Term (CointEq (-1)) proves critical in validating the model's short-run stability and convergence toward long-run equilibrium. Its coefficient of -0.743 signifies that roughly 74.3% of disequilibrium from the prior period corrects within one year, implying the system reverts to equilibrium in approximately 1.345 years. Such rapid adjustment underscores robust short-run dynamics. Short-run ECM results indicate a modest positive association between the digital ecosystem (DES) and CO_2 emissions: a 1-unit DES increase corresponds to a 1.4% emissions rise. This limited-scale effect aligns with Cheng et al. (2019) and Raheem et al. (2020), who attribute emissions growth to digitalization-driven economic expansion and non-renewable energy consumption.

Technological innovation (TI) similarly exhibits a weak positive short-run impact, with a 1-unit increase elevating emissions by 0.021%. This resonates with the Jevons Paradox (1865), wherein efficiency gains lower production costs, spurring higher output and net resource use. Saidi et al. (2020), Khan et al. (2020), and Yang et al. (2021) corroborate this delayed environmental payoff, noting innovation's benefits may initially be offset by industrial scaling. Conversely, renewable energy consumption (REC) demonstrates a potent negative short-run effect: a 1-unit REC increase reduces emissions by 22.5%. This confirms clean energy's immediate environmental benefits, consistent with Baek (2016), Sahoo et al. (2022), Cherni et al. (2017), reinforcing renewables' role in climate mitigation. Financial development (FD) indicates a positive relationship with CO2 emissions, implying a one-unit change in FDI is associated with an increase of CO_2 by 0.651%. This relationship confirms the findings of Khan (2020), Artha et al. (2021), Haini (2021), and Shao et al. (2021), which identified that financial expansion often fuels fossil-fuel-dependent industrial activity. Furthermore, Shahbaz et al. (2021) and Aljadani (2022) diagnosed that unless financial development is directed toward green investments and green technologies, it may continue to degrade environment.

Diagnostic Tests

To find the issues of Heteroscedasticity and autocorrelation, we applied different kinds of test like Bruesch-pagan-Godfrey, Harvey test, Glesjer test and Breusch-Godfrey Serial correlation LM test. To assess the normality of the data Jarque Berra tests was applied. The outcomes are shown in Table 7

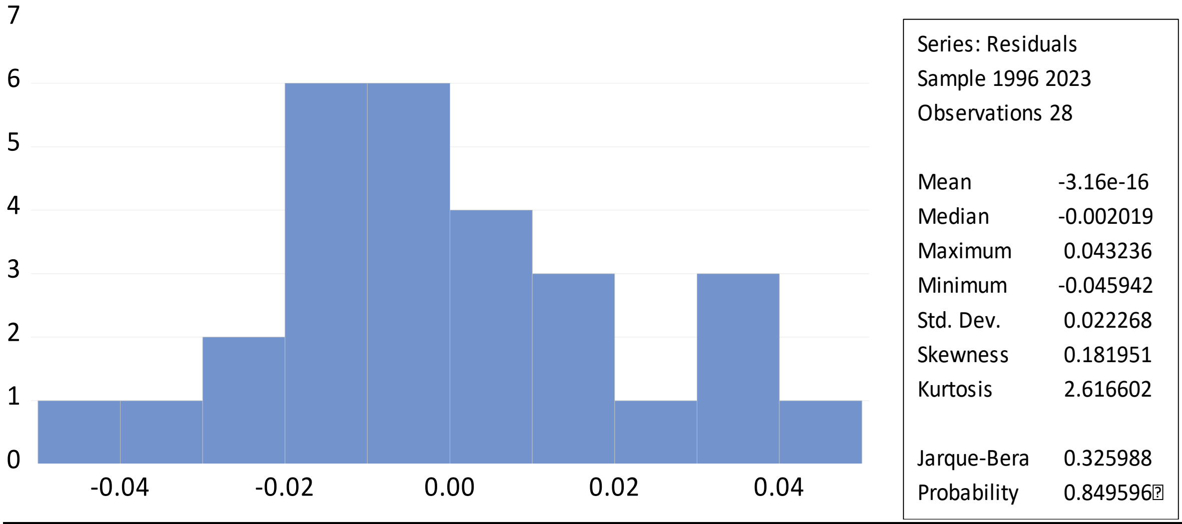
Table 7: Diagnostic tests

Diagnostic tests statistics	P-Value	Results
Heteroscedasticity	0.124 (Bruesch-pagan-Godfrey)	There is No problem of heteroscedasticity
Heteroscedasticity	0.270 (Harvey Test)	There is No problem of heteroscedasticity
Heteroscedasticity	0.379 (Glesjer)	There is No problem of heteroscedasticity
Serial correlation/Autocorrelation	(0.119) Breusch-Godfrey Serial correlation LM test	There is No problem of serial correlation
Normality test (JB-P-value)	0.849	Distribution of the data is normal

Probability value of Bruesch-pagan-Godfrey is 0.124 which is insignificant inditing that there is no problem of Heteroscedasticity. Similarly, Probability value of Harvey test and Glesjer test is also significant in Table 7 which is clearly indicating that there is no problem of Heteroscedasticity. Probability value of Breusch-Godfrey Serial correlation LM test is 0.119 which is insignificant and show that there is no problem of serial correlation

Normality Test

Figure 3: Normal Distribution of data



If we look at the P-value it is 0.849 which is insignificant, it is also showing that the distribution of the data is normal and our model is stable.

Discussion

The overall findings of the study reveal important dynamics in the relationship between CO_2 emissions and key economic and technological variables in Pakistan. The correlation analysis indicates a strong and positive relationship between digital ecosystem expansion, technological innovation, and CO_2 emissions, suggesting that increased use of digital infrastructure and technological progress contribute to higher energy consumption and environmental degradation. In contrast, renewable energy consumption and financial development demonstrate a negative correlation with CO_2 emissions, highlighting their potential roles in mitigating environmental harm when directed toward sustainable applications.

Unit root tests using the Augmented Dickey-Fuller and Phillips-Perron methods confirm the stationarity of the data, ensuring reliable regression outcomes. The bounds test for cointegration validates a long-run equilibrium relationship among the variables, reinforcing the robustness of the ARDL model results. The ARDL long-run estimates show that digital ecosystem development, technological innovation, and financial development significantly contribute to increased CO_2 emissions. This suggests that while these factors can enhance economic growth and efficiency, they also lead to greater fossil fuel consumption unless managed sustainably. On the other hand, renewable energy consumption significantly reduces emissions, emphasizing its vital role in achieving environmental sustainability. Short-run dynamics, captured by the error correction model, indicate that while digitalization, innovation, and financial development still exert a positive influence on emissions, the effects are relatively weaker compared to the long run. Importantly, renewable energy consumption continues to have a strong and immediate negative impact on emissions even in the short term. The error correction term confirms the stability of the model, showing that nearly 74.3% of the disequilibrium is corrected annually, implying a relatively swift adjustment back to equilibrium.

Conclusion

In conclusion, the findings underscore the dual nature of technological and financial progress in influencing environmental outcomes. While these drivers are essential for growth, their environmental costs must be carefully managed. Renewable energy emerges as a crucial solution for reducing emissions, and its promotion should be at the core of environmental and economic planning. A strategic focus on green finance, clean innovation, and sustainable digitalization can enable Pakistan to balance economic development with environmental protection and move toward a more sustainable future

Policy Implications

The study has several important policy implications. Firstly, while digital transformation and technological advancement are crucial for economic modernization, they must be accompanied by policies that promote energy efficiency and low-carbon digital infrastructure. Investments in environmentally friendly technologies and the promotion of green ICT can help mitigate the rebound effects of innovation. Secondly, renewable energy should be further prioritized in Pakistan's energy mix. The strong negative impact of renewable energy on CO_2 emissions in both the short and long run demonstrates its pivotal role in curbing environmental degradation. Expanding subsidies, regulatory support, and infrastructure for solar, wind, and hydroelectric power can accelerate the transition to a cleaner energy future. Thirdly, the positive association between financial development and emissions suggests that financial institutions must be incentivized to channel resources toward green investments. Policymakers should encourage environmental risk assessments in lending practices and support sustainable finance initiatives.

References

- Adebayo, T. S., Akadiri, S. S., Riti, J. S., & Tony Odu, A. (2023a). Interaction among geopolitical risk, trade openness, economic growth, carbon emissions and Its implication on climate change in India. *Energy & Environment, 34*(5), 1305–1326.
- Ahmad, M., Khan, Z., Rahman, Z. U., Khattak, S. I., & Khan, Z. U. (2021). Can innovation shocks determine CO_2 emissions (CO_2e) in the OECD economies? A new perspective. *Economics of Innovation and New Technology, 30*(1), 89-109.
- Ahmad, N., Youjin, L., Žiković, S., & Belyaeva, Z. (2023). The effects of technological innovation on sustainable development and environmental degradation: Evidence from China. *Technology in Society*, 72, 102184. https://doi.org/10.1016/j.techsoc.2022.102184
- Akram, R., Chen, F., Khalid, F., Ye, Z., & Majeed, M. T. (2020). Heterogeneous effects of energy efficiency and renewable energy on carbon emissions: Evidence from developing countries. *Journal of cleaner production, 247*, 119122.
- Alatas, S. (2021). The role of information and communication technologies for environmental sustainability: Evidence from a large panel data analysis. *Journal of environmental management, 293,* 112889.
- Ali, H. S., Sahoo, M., Alam, M. M., Tijjani, I. I. I., Al-Amin, A. Q., & Ahmed, A. (2023). Structural transformations and conventional energy-based power utilization on carbon emissions: Empirical evidence from Pakistan. *Environment, Development and Sustainability, 25*(3), 2419-2442.
- Appiah, M., Li, M., Naeem, M. A., & Karim, S. (2023). Greening the globe: uncovering the impact of environmental policy, renewable energy, and innovation on ecological footprint. *Technological Forecasting and Social Change, 192*, 122561.
- Avom, D., Bangaké, C., & Ndoya, H. (2023). Do financial innovations improve financial inclusion? Evidence from mobile money adoption in Africa. *Technological Forecasting and Social Change*, *190*, 122451.
- Bashir, M. F., Benjiang, M. A., Hussain, H. I., Shahbaz, M., Koca, K., & Shahzadi, I. (2022). Evaluating environmental commitments to COP21 and the role of economic complexity, renewable

energy, financial development, urbanization, and energy innovation: empirical evidence from the RCEP countries. *Renewable Energy, 184*, 541-550.

- Briglauer, W., Köppl-Turyna, M., Schwarzbauer, W., & Bittó, V. (2023). Evaluating the effects of ICT core elements on CO_2 emissions: Recent evidence from OECD countries. *Telecommunications Policy, 47*(8), 102581.
- Celik, A., & Alola, A. A. (2023). Capital stock, energy, and innovation-related aspects as drivers of environmental quality in high-tech investing economies. *Environmental Science and Pollution Research*, *30*(13), 37004-37016.
- Chen, H., Yi, J., Chen, A., Peng, D., & Yang, J. (2023). Green technology innovation and CO_2 emission in China: Evidence from a spatial-temporal analysis and a nonlinear spatial Durbin model. *Energy Policy*, *172,* 113338.
- Chen, X., Rahaman, M. A., Murshed, M., Mahmood, H., & Hossain, M. A. (2023). Causality analysis of the impacts of petroleum use, economic growth, and technological innovation on carbon emissions in Bangladesh. *Energy*, 267, 126565.
- Chen, Y., Wang, Z., & Zhong, Z. (2019). CO_2 emissions, economic growth, renewable and non-renewable energy production and foreign trade in *China. Renewable* energy, 131, 208-216.
- Churchill, S. A., Inekwe, J., Smyth, R., & Zhang, X. (2019). R&D intensity and carbon emissions in the G7: 1870–2014. *Energy* Economics, 80, 30-37.
- Hao, Y., & Chen, P. (2023). Do renewable energy consumption and green innovation help to curb CO_2 emissions? Evidence from E7 countries. *Environmental Science and Pollution Research, 30*(8), 21115–21131.
- Javed, A., & Rapposelli, A. (2024). Unleashing the asymmetric impact of ICT, technological innovation, and the renewable energy transition on environmental sustainability: evidence from Western and Eastern European nations. *Environment, Development and Sustainability,* 1-39. https://doi.org/10.1007/s10668-024-04840-x
- Jiang, Y., & Khan, H. (2023). The relationship between renewable energy consumption, technological innovations, and carbon dioxide emission: Evidence from two-step system GMM. *Environmental Science and Pollution Research, 30*(2), 4187–4202.
- Jianguo, D., Ali, K., Alnori, F., & Ullah, S. (2022). The nexus of financial development, technological innovation, institutional quality, and environmental quality: Evidence from OECD economies. *Environmental Science and Pollution Research, 29*(38), 58179–58200.
- Jin, T., & Kim, J. (2018). What is better for mitigating carbon emissions–Renewable energy or nuclear energy? A panel data analysis. *Renewable and Sustainable Energy Reviews*, *91*, 464-471.
- Kamal, M. A., Ullah, A., Qureshi, F., Zheng, J., & Ahamd, M. (2023). China's outward FDI and environmental sustainability in belt and road countries: does the quality of institutions matter? *Journal of Environmental Planning and Management*, *66*(5), 1002-1036.
- Khan FN, Sana A, Arif U.(2020) Information and communication technology (ICT) and environmental sustainability: a panel data analysis. *Environ Sci Pollut Res* 2020*; 27,* 36718–36731. Khan, M., & Ozturk, I. (2021). Examining the direct and indirect effects of financial development on CO_2 emissions for 88 developing countries. *Journal of environmental management, 293*, 112812.
- Khan, S., Khan, M. K., & Muhammad, B. (2021). Impact of financial development and energy consumption on environmental degradation in 184 countries using a dynamic panel model. *Environmental Science and Pollution Research, 28,* 9542-9557.
- Khattak, S. I., Ahmad, M., Khan, Z. U., & Khan, A. (2020). Exploring the impact of innovation, renew able energy consumption, and income on CO_2 emissions: New evidence from the BRICS economies. *Environmental Science and Pollution Research, 27*(12), 13866–13881.
- Lahiani, A., Shahbaz, M., & Roubaud, D. (2019). Does financial development influence renewable energy consumption to achieve carbon neutrality in the USA? *Energy Policy, 135*, 111052
- Lee, J. W., & Brahmasrene, T. (2014). ICT, CO_2 emissions and economic growth: evidence from a panel of ASEAN. *Global Economic Review, 43*(2), 93-109.

- Mensah, C. N., Long, X., Dauda, L., Boamah, K. B., Salman, M., Appiah-Twum, F., & Tachie, A. K. (2019). Technological innovation and green growth in the Organization for Economic Cooperation and Development economies. *Journal of Cleaner Production*, *240,* 118204.
- Mohsin, M., Kamran, H. W., Nawaz, M. A., Hussain, M. S., & Dahri, A. S. (2021). Assessing the impact of transition from nonrenewable to renewable energy consumption on economic growth-environmental nexus from developing Asian economies. *Journal of environmental management, 284,* 111999.
- Mukhtarov, S., Karacan, R., & Humbatova, S. (2024). The long-run effect of financial development on carbon emissions in Kazakhstan. *Energy Efficiency, 17*(3), 17.
- Paramati, S. R., Mo, D., & Huang, R. (2021). The role of financial deepening and green technology on car bon emissions: Evidence from major OECD economies. *Finance Research Letters, 41,* 101794.
- Qudrat-Ullah, H. (2023). A Review and Analysis of Green Energy and the Environmental Policies in South Asia. *Energies*, 16(22), 7486.
- Sahoo, M., & Sahoo, J. (2022). Effects of renewable and non-renewable energy consumption on CO_2 emissions in India: empirical evidence from disaggregated data analysis. *Journal of Public Affairs, 22*(1), e2307.
- Saidi, K., & Omri, A. (2020). The impact of renewable energy on carbon emissions and economic growth in 15 major renewable energy-consuming countries. *Environmental research, 186,* 109567.
- Saleem, H., Khan, M. B., & Mahdavian, S. M. (2023). The role of economic growth, information technologies, and globalization in achieving environmental quality: a novel framework for selected Asian countries. *Environmental Science and Pollution Research*, 30(14), 39907-39931.
- Shahbaz, M., Nasir, M. A., & Roubaud, D. (2018). Environmental degradation in France: the effects of FDI, financial development, and energy innovations. *Energy economics*, 74, 843-857.
- Shao, J., & Huang, P. (2023). The policy mix of green finance in China: an evolutionary and multilevel perspective. *Climate Policy*, *23*(6), 689-703.
- Shao, Y., Li, J., & Zhang, X. (2022). The impact of financial development on CO_2 emissions of global iron and steel industry. *Environmental Science and Pollution Research, 29*(29), 44954-44969.
- Streimikiene, D. (2024). Renewable energy penetration in Nordic and Baltic countries of the EU. *Journal of International Studies*, *17*(1), 97-107.
- Ullah, S., Adebayo, T. S., Irfan, M., & Abbas, S. (2023). Environmental quality and energy transition prospects for G-7 economies: The prominence of environment-related ICT innovations, financial and human development. *Journal of Environmental Management, 342,* 118120.
- Usman, M., Balsalobre-Lorente, D., Jahanger, A., & Ahmad, P. (2022). Pollution concern during globalization mode in financially resource-rich countries: do financial development, natural resources, and renewable energy consumption matter? *Renewable* energy, 183, 90-102.
- Wang, W., Tang, Q., & Gao, B. (2023). Exploration of CO_2 emission reduction pathways: identification of influencing factors of CO_2 emission and CO_2 emission reduction potential of power industry. *Clean Technologies and Environmental Policy, 25*(5), 1589-1603.
- Wenlong, Z., Tien, N. H., Sibghatullah, A., Asih, D., Soelton, M., & Ramli, Y. (2023). Impact of energy efficiency, technology innovation, institutional quality, and trade openness on greenhouse gas emissions in ten Asian economies. *Environmental science and pollution research*, *30*(15), 43024-43039.
- Yang, X., Jia, Z., Yang, Z., & Yuan, X. (2021). The effects of technological factors on carbon emissions from various sectors in China—A spatial perspective. *Journal of Cleaner Production, 301*, 126949.
- Wu, S., Wu, Z., Gao, Z., Awan, A. G., & Sumra, B. (2024). Green energy resources, products recycling, and clean environment. *The Journal of Environment & Development*, *33*(2), 175–195. https://doi.org/10.1177/10704965231217048