Impact of Digitalization and Renewable Energy on Environmental Quality in Pakistan

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Abstract

This study examines how digitalization and renewable energy affect environmental quality in Pakistan, using time series data from 1996 to 2023. It uses robust econometric techniques: the Augmented Dickey-Fuller (ADF) unit root test, ARDL bounds testing, and short- and long-run ARDL models. The unit root test found a mix of I(0) and I(1) variables, making ARDL appropriate. The ARDL bounds test confirmed a long-run cointegration between environmental quality and the chosen variables. ARDL long-run estimates indicate that renewable energy and digitalization are negatively and significantly associated with environmental degradation. In contrast, industrialization and population growth are positively linked to environmental degradation. These results reveal the potential for digital and clean energy technologies to drive sustainable development and highlight the need to green the industrial sector and align financial systems with environmental goals.

Keywords: Environmental Quality, Digitalization, Renewable Energy, ARDL Model.

Introduction

Recently, some of the most debatable issues worldwide have been ecological imbalances, climate disturbances, environmental degradation (ED), and climate change. Rapid industrialization and economic expansion lead to a heavy reliance on natural resources and conventional energy sources, which degrade ecosystems by increasing waste and other environmental pollutants (Usman et al., 2021). The main cause of these deteriorations is carbon dioxide (CO2) emissions, reflecting the general concern for environmental quality.

The majority of our everyday activities now rely heavily on contemporary computers and digital technology as the world enters a period of digitization. Socioeconomic, environmental, sustainability, and climatic research can apply these modern technologies to increase the production and efficiency of systems (Awan, 2013; Balogun et al., 2020; Ceipek et al., 2021). It is expected that digitization will extend the lifespan of existing energy infrastructure, enabling better electricity distribution and use in more distant areas. However, we must also be prepared for the possibility of digitization, which may introduce new problems into the established energy infrastructure (Bashir & Awan, 2025). The development of smart technologies connected to the internet provides an opportunity to address questions about the Sustainable Development Goals

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(SDGs), which are set by the UN to create a healthy, environmentally stable society. According to this viewpoint, digitization helps to create a society that will be sustainable in the future (Xu et al., 2022).

Raising environmental norms requires digitalization. Increasing digitalization, for example, significantly enhances environmental quality by reducing carbon and GHG emissions, as well as other pollutants, according to empirical studies by Garske et al. (2021) and Wei & Ullah (2022). Enhancing technical innovation through digitalization leads to more energy-efficient resource use, lower energy demand (fossil fuels), and ultimately lower emissions and other pollution levels. Furthermore, digitalization (DGI) promotes green globalization, boosts the eco-friendly products' export value (Thanh, 2022), encourages green total energy efficiency (Gao et al., 2022), and shrinks the production scale of companies that generate a lot of pollution (Awan, 2013; Wen et al., 2021).

On the other hand, a sustainable environment is produced through the utilization of renewable energy (Awan, 2015). By concentrating on renewable energy and sustainable growth, an emission-free environment can be achieved. One possible way to establish and implement a sustainable environment is to adopt and use green energy and technologies. Environmental sustainability is the outcome of sustainable energy solutions. It can be highly advantageous to use renewable energy sources, i.e., solar, tidal, wind, and biomass. As a result, spending on renewable energy is more sustainable and favorable to the environment than using fossil fuels (Midilli et al., 2006). Renewable energy is therefore essential to halting environmental deterioration in developing nations.

Problem Statement

The global economy is being negatively affected by poor environmental quality. As a result, several countries have allocated significant income to mitigate risks. If these environmental issues didn't exist, funds designated to address them could be used to achieve other crucial economic goals (Ali et al., 2019). Environmental degradation is a major challenge facing Pakistan, with rising pollution levels, deforestation, and climate change posing serious threats to public health, economic growth, and biodiversity. To this effect, digitalization and renewable energy have been advanced as possible mechanisms to champion environmental sustainability. Nonetheless, it is unclear how these factors have affected Pakistan's environmental quality. The development of renewable energy (RE), especially solar, wind, and hydropower, is on the rise. The targets Pakistan has set to increase its share of RE are ambitious, and the country hopes to reduce its reliance on fossil fuels. Nevertheless, the pace of progress has been slackened by difficulties in funding, policy execution, and grid connection. It is unclear to what extent renewable energy projects have improved environmental indicators such as carbon emissions and air quality.

The interaction between digitalization and renewable energy creates synergies that boost environmental benefits. However, these technologies can introduce new environmental risks if not managed carefully. This analysis addresses the lack of in-depth evidence on how DGI and RE impact environmental quality (EQ) in Pakistan. Understanding these effects is crucial for creating policies that maximize environmental benefits and minimize side effects, moving Pakistan toward a sustainable, resilient future.

Objectives of the Study

This study mainly examines how digitalization and renewable energy affect Pakistan's environmental quality. Specifically, it aims to:

- To investigate the impact of digitalization on the quality of the environment in Pakistan
- To examine the impact of renewable energy on Pakistan's environmental quality

Research Questions

The study tests these research questions:

- Does digitalization affect environmental quality in Pakistan?
- Does renewable energy affect environmental quality in Pakistan?

Significance of the Study and Research Gap

Digitalization and RE have a considerable influence on EQ. Various studies have examined the role of RE and digitalization in shaping environmental quality; however, the literature remains divided on how these factors affect EQ, particularly in Pakistan. Similarly, very few studies, especially in Pakistan, were available that analyze the nexus between RE, digitalization, and EQ. Therefore, this analysis is significant because it will provide new insights into how digitalization and renewable energy are crucial to improving Pakistan's environmental quality. The study will consider various indicators of digitalization, such as the number of internet users, mobile phone subscriptions, and ICT expenditures, and link these factors to environmental quality. The moderation of digitalization and renewable energy will also be analyzed to see the combined influence of these aspects on the environment in Pakistan. This analysis will help policymakers develop environmental policies that account for digitalization and renewable energy.

Literature Review

Studies on the Impact of Digitalization on Environmental Degradation

Mehmood et al. (2023) examined the relationships among digitalization (DGI), technological advancement, RE, economic growth (EG), and financial development (FD). Using G8 data from 1990 to 2018, the study analyzed the data with the CS-ARDL model and a cointegration test. The data indicated that renewable energy (RE), technological advancement, and digitization were all beneficial to natural health. According to the study, the G8 government must prioritize environmental policies that boost economic expansion, expand the use of RE, focus technological advancement in key areas, and encourage the creation of more ecologically friendly digital ICT technologies. Ren et al. (2023) interrogated the impact of internet development on EQ in China by using data from 30 provinces from 2006 to 2017. The outcomes revealed that ED in China has a substantial regional spillover effect. The development of the Internet can significantly reduce environmental degradation, not only locally but also regionally. The mediation effect's regression results showed that increasing technological innovation, industrial upgrading, financial development, and human capital have a substantial influence on declining ED. Damrahe al. (2022) examined the effects of ICT use on ED and its moderating function in the relationship between financial inclusion and ED. Data from 1995 to 2019 from six oil-exporting nations was used in the analysis. The outcomes revealed that carbon intensity is greatly enhanced by energy use. The empirical findings revealed that the six oil-exporting economies had the capability to protect the environment through mobile and Internet use, as measures of ICT use. The research also found that financial inclusion contributed to environmental conservation by reducing emissions.

Ma et al. (2022) explored the link between digitalization and ED in 30 regions of China from 2006 to 2017. The results showed long-run cointegration among R&D expenditures, digitalization, carbon dioxide emissions, and other significant macroeconomic factors. Digitalization was also

shown to reduce provincial emission rates. Zafar et al. (2022) analyzed how ICT and education affect the EQ. This study relied on data from Asian countries between 1990 and 2018, and used the FMOLS method to analyze them. The findings revealed that an increase in EG was associated with higher energy demand. This paper concludes that education is a driver of ICT innovation, but without RE, ICT innovation in Asia worsens the environmental situation. Huong & Thanh (2022) studied the impacts of DGI on ED using a 25-country database covering the period 2015-2020 in Europe. The results indicate that the digital transformation process enhances EQ primarily in digital skills, company DGI, and digital public services. The importance of digital connection, digital skills, and business DGI to ecosystem vitality and the effect of digital public services and corporate DGI to environmental health were also highlighted in the study.
Usman et al. (2021) examined the influence of ICT on ED across 9 Asian economies from 1990 to 2018. The paper analyzed the asymmetric impacts of ICT on ED. Findings indicated that the number of countries in which ICT has a considerable impact on CO2 emissions has remained stable. The results indicated a skewed effect of ICT use on environmental degradation in some Asian economies. The results found that the development of positive trends in ICT contributed to the reduction of environmental degradation in Asian countries. Li et al. (2021) discussed the association between the digital economy and ED. To this end, the model employed a fixed-effects panel data model for 190 countries over the period 2005-2016. The digital economy was incorporated into the Solow growth model in the study. Based on the findings, the association between the digital economy and ED was inverted U-shaped, and the square form of the former was negative and significant. Charfeddine and Kahia (2021) examined the influence of ICT and REC on EQ in the MENA region using statistical data from 1980 to 2019. The study used a panel vector autoregressive model in data estimation. The results advocated that the ED was a consequence of ICT application in the present economic development scenario of the MENA region. The findings also demonstrated that the REC improves environmental conditions. The study's causality analysis showed a two-way relationship between ED and the use of ICT and RE. To enhance EQ, the report proposed that MENA countries promote ICT growth.

Studies on the Impact of Renewable Energy on Environmental Degradation

Nan et al. (2022) explored the impact of REC on energy EF employing the quantile regression approach. The findings exhibited that RE has a detrimental long-term effect on the EF. Energy EF and renewable energy use did not exhibit a two-way Granger Causal relationship. Wind energy consumption shows the largest decrease in energy EF, followed by photovoltaic and biomass. Moreover, the influence of biomass, wind, and photovoltaic energy consumption on EF varied across different distribution parameters. Kartal et al. (2022) investigated the cumulative and the disaggregated influence of EC on ED. This study focuses on the USA, the largest economy and the second-largest emitter of carbon dioxide (CO2). The research used a nonlinear method, Wavelet Coherence (WC), with data collected between 1989 and 2021. The results showed that EC has a substantial impact on ED in the short-, medium-, and long-term. Hence, the findings indicate the significance of renewable energy application in enhancing EQ and reducing overall CO2 emissions, as well as CO2 emissions separately. Literature used PMG methodology and the Granger causality test to analyze the impacts of EC on EQ in the MINT nations between 1971 and 2017. The outcomes confirmed that the factors applied were long-run related. The results also revealed that in the long run, EG, EC, and biocapacity positively and statistically significantly impact environmental degradation. This implies that EC has a negative effect on the ecological footprint, which deteriorates the quality of the environment. The results also indicated that the EQ would worsen due to increased ecological footprints, as the MINT countries would use more energy to accelerate EG.

Khan et al. (2021) analyzed how tourism, trade openness, FDI, and REC influence carbon emissions in both developed and developing nations between 1985 and 2018. Based on the results of system GMM, renewable energy negatively and significantly affects carbon emissions in both developed and developing nations. Safdar (2020) examined the long-term association among EC, ED, and macroeconomic performance in a select group of emerging nations. Fifty developing nations were chosen for this purpose between 1990 and 2016. EC, ED, labor force participation, GCF, remittances, the manufacturing sector, GDP, and employment were chosen as stand-in indicators of macroeconomic performance. The findings indicated that all variables in a few chosen emerging nations have cross-sectional dependencies. The study utilized a panel of nine Mediterranean economies from 1980 to 2014 to explore the causal link between GDP, ED, and EC. CSD and heterogeneity among the panel were considered to explore the validity of a proposed model and the long- and short-term dynamic relations with the PMG panel ARDL and panel econometric tools. The results provided panel empirical support on the short-term bidirectional causality between GDP, green energy use, and ED, and between GDP and green electricity use and nonrenewable power use. The outcomes of the long-term causal association revealed that the electricity use in non-renewable sources and CO2 emissions were causally related in both directions.

Appiah (2018) examined the link between the EG of Ghana, EC, and ED. This study used data from 1960 to 2015. The results confirmed the relationship among ED, EG, and EC. The outcomes of the causality tests indicated a causal association between ED, EC, and EG. Nevertheless, the causal association between the ED, EG, and EC also existed. Inglesi-Lotz & Dogan (2018) used panel estimation methods robust to cross-dependencies to determine the determinants of ED for the ten largest electricity generators in SSA from 1980 to 2011. It has been confirmed that the major variables have a long-term relationship. Pollution increases when NREC rises, but RE has the reverse effect. The analysis found a unidirectional causal association between emissions, trade, income, NRE, and renewable energy sources; NRE sources and ED; and ED and non-renewable energy sources and trade. Studies employed the EKC framework to study the relationships between ED, real GDP, the square of real GDP, EC, trade, and tourism for Members of the OECD using data from 1995 to 2010. According to the dynamic ordinary least squares (DOLS) estimation technique, while trade growth results in environmental gains, EC and tourism are responsible for the levels of petrol emissions. Furthermore, the GDP and GDP2 coefficients had negative and positive signs, respectively, making the EKC hypothesis unsupportable. Mert & Bolt (2016) examined how FDI and the potential for RE use influence ED in 21 Kyoto countries. The EKC hypothesis was assessed using panel cointegration analysis. The outcomes indicated a long-term causal relation between the variables and ED, REC, the use of fossil fuels, and FDI inflows. The outcomes confirmed the concept of pollution halo, which posits that FDI improves the environmental standards and brings clean technologies.

A growing body of literature has examined the roles of digitalization and renewable energy in environmental sustainability, often highlighting their capacity to either reduce or exacerbate environmental degradation depending on context and implementation. Numerous studies have investigated these dynamics in developed economies (e.g., Mehmood et al., 2023) and emerging global regions such as BRICS and MENA countries (Charfeddine & Kahia, 2021). These studies largely agree that while digitalization can reduce carbon emissions and improve ecological outcomes, it may also have short-term adverse effects if not coupled with green infrastructure or renewable energy use. Similarly, renewable energy has been found to significantly mitigate environmental degradation, though challenges such as land use, material sourcing, and policy barriers remain. However, there is a significant lack of country-specific research focusing on Pakistan, a nation experiencing both rapid digital expansion and growing energy demands. Most existing studies either aggregate developing countries into broader regional analyses or focus on advanced economies, overlooking the distinct socio-economic, technological, and environmental conditions in Pakistan. Moreover, although some literature addresses EC and CO_2 emissions in Pakistan, the combined effects of digitalization and renewable energy adoption on environmental sustainability remain underexplored.

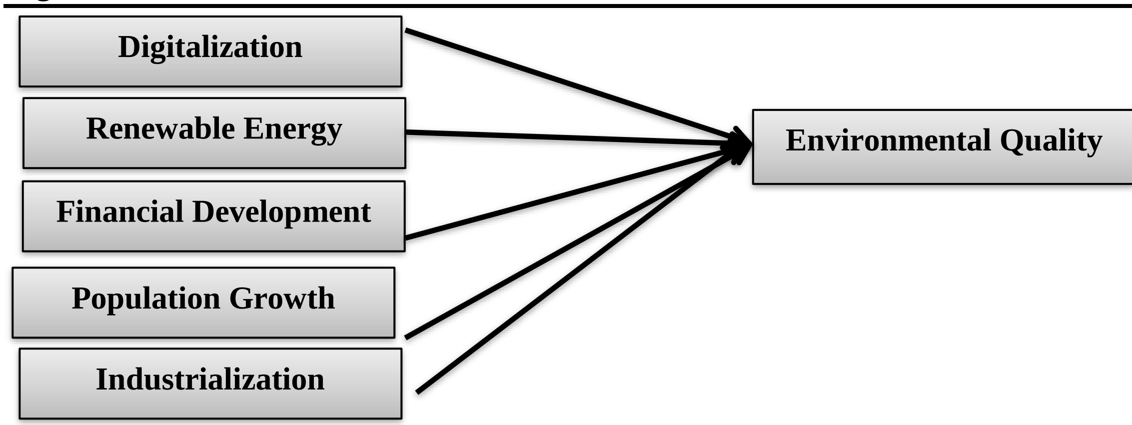
Hypotheses Development

Following the association between digitalization and RE, the following hypotheses are developed:
H1: Digitalization is positively and significantly associated with the environmental quality.
H2: Green energy is positively and significantly associated with environmental quality.
H3: Financial development is significantly associated with environmental quality.
H4: Industrialization is negatively and significantly associated with environmental quality.
H5: Population growth is negatively and significantly associated with environmental quality.

Conceptual Framework

Based on the studies of variables, the hypotheses, and the reviewed literature, the following conceptual model is developed and shown in Figure 1.

Figure 1: Research Model



Methodology

This study analyzes the influence of DGI and renewable energy on environmental quality of Pakistan. For this purpose, the study used the yearly data from 1996 to 2023. The data of all the variables are collected from the world development indicators.

Model Specification

To examine the influence of digitalization and renewable energy on environmental quality in Pakistan, the dependent variable used in a study is CO_2 emissions, though the core explanatory variables are DGI and REC. The control variables incorporated in a model are industrialization, financial development and population growth. Control variables include industrialization and financial development to consider their structural and financial effects on the environmental quality and eliminate the bias of omitted variables. Industrialization embodies the activities of pollution-based production and financial development covers the functions of credit and investment in technological innovations and green financing. The inclusion assures that the estimated coefficient of digitalization and renewable energy take into consideration their net and unbiased impact. The following model is developed for data estimation:

$$EQ_i = \beta_o + \beta_1 DGI_i + \beta_2 REC_i + \beta_3 FD_i + \beta_4 IND_i + \beta_5 PGR_i + \beta_6 REC * DGI_i + u_i$$

Where EQ is the environmental quality, DGI is the digitalization index, REC is the renewable energy consumption, FD is the financial development, PGR is the population growth rate, REC*DGI is the interaction term and u_i is the error term. Based on the complementarity and innovation diffusion models, an interaction term between digitalization and renewable energy is added to introduce their synergistic relationship with environmental quality. Digitalization enhances efficiency and control of renewable energy infrastructures via smart grids, real-time monitoring and energy optimization and the renewable energy minimizes carbon footprint of digital infrastructure. Thus, the interaction term will enable us to test the hypothesis of whether the difference between the effects of digitalization and renewable energy is bigger than their respective effects.

Table 1: Description of Variables

Variables	Description of Variables	
	Dependent Variable	
EQ	Environmental quality	CO_2 Emissions
	Independent Variables	
DIG	Digitalization	Index using digitalization indicators number of internet users and number of cellular phone subscriptions (Based on the studies Ullah et al., 2024; Li et al., 2021).
RE	Renewable energy	Percentage of total energy consumption
FD	Financial development	Domestic credit to private sector as a percentage of GDP
IND	Industrialization	Industry value added as a percentage of GDP
PGR	Population Growth	Growth Rate Annual

Analytical Techniques

In this analysis, various econometric techniques are applied for data estimation. The explanation of the techniques is given as follows:

ADF Unit Root Test

It is significant to explore the unit root of the time series data for the long-run analysis and long-run outcomes. In this phase, we analyzed whether data is stationary or not. If the time series data for Pakistan has a constant mean, variance, and co-variance then this is known as stationary of time series data. On the other hand, if the time series data has no constant mean, variance, and co-variance then it is known as not stationary of the data. Time series is the best for the long-run analysis of study. Unit root data produced spurious results which estimate the coefficients are

correlated to other variables or coefficients. If an economist wants to avoid the spurious results of time series data, then it is need to apply the unit root tests.
It is the most famous unit root test for examining the stationarity of the time-series data. It is the extended form of the dickey fuller test which is presented before the augmented dickey fuller test. The dickey fuller test is simply different from the augmented dickey fuller test because it excludes the element of autocorrelation in the time series data empirically analysis. Due to this reason, an augmented dickey fuller test is used for the unit root analysis. It has the facility to examine the unit root of the time series data with different lags. But this lag facility not provided by the dickey fuller test.
The null hypothesis and alternative hypothesis of the ADF test are as follows:
H_o: Non-stationary series
H_1: Stationary series
The ordinary least square (OLS) is employed when all model variables are stationary at I(0). If all model variables are stationary on the initial difference I(1), ARDL is optimum for long-run estimation. The ARDL model is ideal for long-term estimation analysis if some variables are stationary on the level and some on the initial difference.

Bound Test
We must observe the long-run relationship between variables when doing the bound test. Time series co-integration analysis uses the bound test. Long-term variable relationships are examined using the bound test. The bound test has two essential values: upper and lower bond values. Bound test hypotheses:
H_o: No cointegration among the series
H_1: cointegration exists between the series
All the coefficients of the bound test are not equal to zero. If the F-statistic value is greater than the value of upper bound, then there is cointegration that exists between the series.

Autoregressive Distributed Lag (ARDL) Model
The ARDL model is presented by the Pesaran (1999). After Pesaran, this technique is extended by Pesaran (2002). The ARDL model avoids the uncertainty which exists in the other techniques. Other techniques required not the unit root of all variables on the level and first difference. In the small sample, the ARDL model is favorable and this approach is changeable. The use of the ARDL model provides the existence and evidence of the long-run relationship with the help of a bound test.
The bound test approach co integration provides the following econometric advantages over other methods:

- It is assumed that every variable in the model is endogenous.
- The bounds test method for cointegration is used regardless of the variable's order of integration. Either integrated first order I (1) or λ (0) may exist.
- The model's long-term and short-term coefficients are computed concurrently.

The long-run form of the ARDL models is given as follows:

$$\Delta(EQ)_t = \alpha + \beta_1(EQ)_{t-1} + \beta_2(DIG)_{t-1} + \beta_3(RE)_{t-1} + \beta_4(FD)_{t-1} + \beta_5(IND)_{t-1} + \sum_{i=1}^{a_1} \delta_1 \Delta(EQ)_{t-i} + \sum_{i=0}^{a_2} \delta_2 \Delta(DIG)_{t-i}$$
$$+ \sum_{i=0}^{a_3} \delta_3 \Delta(RE)_{t-i} + \sum_{i=0}^{a_4} \delta_4 \Delta(FD)_{t-i} + \sum_{i=0}^{a_5} \delta_5 \Delta(IND)_{t-i} + \sum_{i=0}^{a_5} \delta_6 \Delta(PGR)_{t-i} + \varepsilon_t$$

The short-run error correction form of the ARDL models is given as follows:

$$\Delta(EQ)_t = \alpha + \sum_{i=1}^{a_1}\lambda_1\Delta(EQ)_{t-i} + \sum_{i=0}^{a_2}\lambda_2\Delta(DIG)_{t-i} + \sum_{i=0}^{a_3}\lambda_3\Delta(RE)_{t-i} + \sum_{i=0}^{a_4}\lambda_4\Delta(FD)_{t-i} + \sum_{i=0}^{a_5}\lambda_5\Delta(IND)_{t-i} + \sum_{i=0}^{a_6}\lambda_6\Delta(PGR)_{t-i} + \omega ECM_{t-1} + \varepsilon_t$$

Data Analysis

Descriptive Statistics

Table 2 indicates that the mean values of Environmental Quality, Digitalization, Renewable Energy, Industrialization, Financial Development and Population Growth in Pakistan are 0.726, 0.104, 46.794, 19.836, 18.430 and 2.114, respectively. Similarly, the maximum values of EQ, DGI, REC, IND, FD and PGR in Pakistan are 0.918, 2.913, 52.170, 22.103, 25.474 and 3.092, respectively. In contrast, the minimum values of Environmental Quality, Digitalization, Renewable Energy, Industrialization, Financial Development and Population Growth in Pakistan are 0.620, -1.583, 39.944, 17.159, 13.878 and 1.204, respectively. The distributions of EQ, DGI, FD and Population Growth are positively skewed whereas the Renewable Energy and Industrialization have a negatively skewed distribution. Lastly, the kurtosis value of the variables indicates that the distribution is platykurtic.

Table 2: Descriptive Statistics

Variables	Mean	Maximum	Minimum	Std. Dev.	Skewness	Kurtosis
EQ	0.726	0.918	0.620	0.080	0.460	2.562
DGI	0.104	2.913	-1.583	1.499	0.265	1.634
REC	46.794	52.170	39.944	3.658	-0.188	1.979
IND	19.836	22.103	17.159	1.566	-0.227	1.905
FD	18.430	25.474	13.878	4.010	0.571	1.747
PGR	2.114	3.092	1.204	0.568	0.283	2.125

Correlation Analysis

This section explains the correlation analysis. The outcomes point out that the environmental quality as measured by CO_2 emissions are negatively correlated with the Digitalization, RE, and FD whereas the CO_2 emissions are positively correlated with the Industrialization and Population Growth in Pakistan.

Table 3: Correlation Analysis

Correlation	EQ	DGI	REC	IND	FD	PGR	DGI_REC
EQ	1.000						
DGI	-0.659	1.000					
REC	-0.782	-0.896	1.000				
IND	0.192	-0.051	0.150	1.000			
FD	-0.381	-0.725	0.522	0.492	1.000		
PGR	0.813	-0.776	0.742	0.149	0.643	1.000	
DGI_REC	-0.685	0.997	-0.893	-0.037	-0.727	-0.807	1.000

ADF Unit Root Analysis

Table 4 presents the ADF unit root test results. The variables EQ, FD, and Population Growth are stationary at level, indicating they are integrated of order zero, I(0). Conversely, DGI, REC, and IND become stationary only after first differencing, implying they are integrated of order one, I(1). These results suggest a mix of I(0) and I(1) variables, justifying the use of econometric models like ARDL, which can accommodate variables with different levels of integration but not I (2).

Table 4: ADF Unit Root Analysis

Variables	Level		1st Difference		Outcomes
	Level	Prob.	Level	Prob.	
EQ	-4.010	0.024	--	--	I(0)
DGI	--	--	-4.498	0.002	I(1)
REC	--	--	-4.719	0.001	I(1)
IND	--	--	-5.150	0.000	I(1)
FD	-4.048	0.023	--	--	I(0)
PGR	-3.123	0.039	--	--	I(0)

Bound Test Analysis

Table 5 presents the ARDL bounds test for cointegration. The calculated F-statistic (7.6915) exceeds the upper bound critical values at all significance levels (1%, 2.5%, 5%, and 10%). This indicates strong evidence to reject the H_o of no long-run association among the variables. Therefore, a significant long-run equilibrium relationship exists between EQ, DGI, REC, IND, FD and PGR, justifying the use of an ARDL model for further analysis of both long-run and short-run dynamics.

Table 5: ADF Unit Root Analysis

Null Hypothesis: No long-run relationships exist		
Test Statistic	**Value**	**k**
F-statistic	7.6915	6
Critical Value Bounds		
Significance	**I0 Bound**	**I1 Bound**
10%	2.12	3.23
5%	2.45	3.61
2.5%	2.75	3.99
1%	3.15	4.43

ARDL Long-Run Analysis in Pakistan

Table 6 presents the long-run coefficients estimated through the ARDL model, with ED as the dependent variable. The coefficient for digitalization is -0.4789, and it is statistically significant at the 1% level (p = 0.0003). This negative relationship implies that increased digitalization reduces environmental degradation in the long run. This suggests that advancements in digital technologies may be fostering energy efficiency, improving environmental monitoring, and promoting smart systems (e.g., smart grids, green IT solutions) that help reduce emissions and pollution. Digitalization may also facilitate the dissemination of environmental awareness and adoption of sustainable practices in industry and society. These findings are also found by Zia et al., (2023). RE also shows a significant negative coefficient of -0.0254 (p = 0.0054), indicating that increased reliance on RE sources contributes to a reduction in ED. This aligns with theoretical expectations, as renewables such as solar, wind, and hydropower are cleaner alternatives to fossil fuels. The result supports the notion that transitioning to renewable energy can help Pakistan reduce carbon emissions and mitigate the adverse impacts of environmental pollution in the long run. These findings are also found by Suki et al. (2022).

The coefficient of industrialization is 0.0168 and statistically significant at the 5% level (p = 0.0219), indicating a positive relationship with ED. This implies that industrial expansion contributes to environmental harm, possibly through increased emissions, resource depletion, and waste generation. This finding suggests that Pakistan's industrial growth is not yet environmentally sustainable, potentially due to outdated technologies, weak regulatory frameworks, and limited environmental compliance among industries. Financial development has a negative coefficient of -0.0053, but it is not statistically significant (p = 0.3349). This suggests that while financial development might be expected to promote investment in green technologies or support sustainable projects, in Pakistan's case, it does not have a measurable long-term impact on environmental degradation. This could reflect insufficient targeting of environmental projects within the financial sector or a lack of effective environmental risk assessment in lending decisions (James & Awan, 2019). Population growth is positively related to environmental degradation, with a coefficient of 0.0070, but this result is also statistically insignificant (p = 0.7502). The lack of significance suggests that population growth, in isolation, does not have a decisive long-term effect on EQ. This might be due to mixed effects while more people can strain resources and increase pollution, they can also contribute to innovation, human capital, and environmental activism, balancing out the impact. These findings are also found by Aiyetan and Olomola, (2017); Kanwal and Awan, (2026). The interaction term between digitalization and REC (DGI_REC) has a strong and highly significant negative coefficient of -1.0269 (p = 0.0002). This indicates that when digitalization and renewable energy increase together, their combined effect leads to a substantial reduction in environmental degradation. This synergy may reflect how digital tools can enhance the efficiency, distribution, and integration of renewable energy sources such as through smart grids, predictive maintenance, and real-time data analytics thereby maximizing environmental benefits.

Table 6: ARDL Long-Run Results

ARDL Long Run Form				
Dependent Variable: Environmental Degradation				
Variable	Beta	S.E	T-Test	Prob.
DIG	-0.4789	0.0973	-4.9199	0.0003
RE	-0.0254	0.0076	-3.3340	0.0054
IND	0.0168	0.0064	2.6030	0.0219
FD	-0.0053	0.0053	-1.0013	0.3349
PGR	0.0070	0.0216	0.3252	0.7502
DIG_RE	-1.0269	0.1982	-5.1802	0.0002
C	2.3544	0.4083	5.7653	0.0001

ARDL Short-Run Analysis

Table 7 presents the ARDL cointegrating form results, analyzing the short-run dynamics and speed of adjustment toward long-run equilibrium for Environmental Degradation as the dependent variable. The error correction term, CointEq(-1), has a value of -0.9200 (p = 0.0001), indicating a strong and statistically significant adjustment toward long-run equilibrium. This means that approximately 92% of the previous period's deviation from equilibrium is corrected in the current period, reflecting a stable and quickly adjusting system. The lagged dependent variable D(EQ(-1)) is positive and significant (0.2962, p = 0.0370), indicating that past environmental conditions positively influence current degradation, showing some persistence over time. Digitalization (DGI) has a significant and negative impact (-0.4407, p = 0.0003), suggesting that increased digitalization contributes to reducing environmental degradation in the short run. This may be due to improved monitoring, energy efficiency, and smart technologies. Renewable energy consumption (REC) also shows a negative and significant effect (-0.0233, p = 0.0006), indicating that a greater reliance on renewable energy sources helps mitigate environmental harm in the short term. Industrialization (IND), with a coefficient of 0.0154 (p = 0.0474), has a significant positive impact, implying that short-run increases in industrial activity exacerbate environmental degradation, likely due to pollution and resource consumption. Financial development (FD) and population growth (PGR) both show statistically insignificant effects (p = 0.2893 and 0.7569, respectively), indicating they do not significantly influence environmental degradation in the short run. Lastly, the interaction term DIG_REC is positive and significant (0.9448, p = 0.0008), suggesting that although digitalization and renewable energy individually reduce degradation, their combined short-run effect may lead to increased environmental pressure perhaps due to inefficiencies in integration or transitional energy demand. The positive effect of short-run interaction (DIG*REC) can be due to transitional adjustment costs and rebound effects related to the implementation of digital energy infrastructure and renewable energy infrastructure, but the negative effect on the long-run means synergistic environmental benefits as the systems become more developed.

Table 7: ARDL Short-Run Results

ARDL Cointegrating Form				
Dependent Variable: Environmental degradation				
Cointegrating Form				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(EQ(-1))	0.2962	0.1275	2.3230	0.0370
D(DGI)	-0.4407	0.0914	-4.8205	0.0003
D(REC)	-0.0233	0.0052	-4.4840	0.0006
D(IND)	0.0154	0.0070	2.1894	0.0474
D(FD)	-0.0048	0.0044	-1.1047	0.2893
D(PGR)	0.0064	0.0204	0.3161	0.7569
D(DGI_REC)	0.9448	0.2162	4.3695	0.0008
CointEq(-1)	-0.9200	0.1590	-5.7832	0.0001

Model Diagnostic Analysis

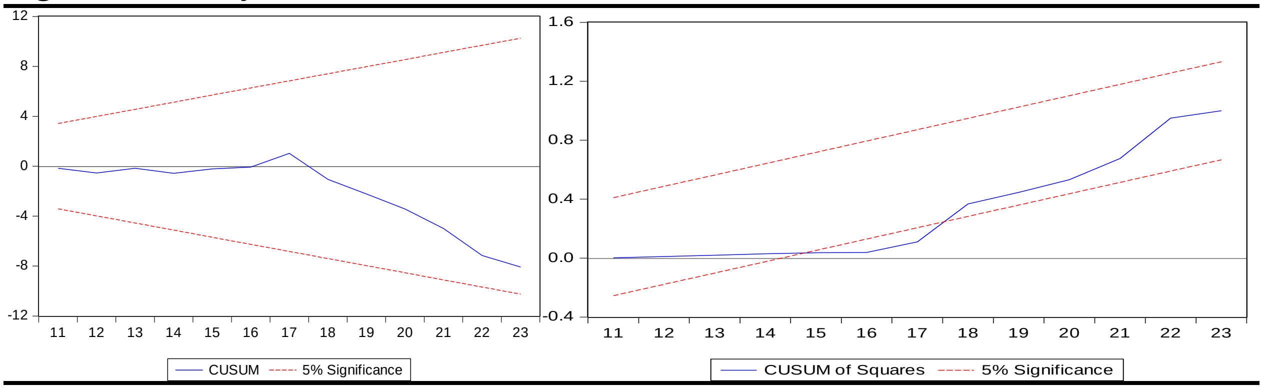
Table 8 presents the outcomes of different model diagnostic tests. The findings show that model is proven reliable using diagnostic tests and it had no specification errors, autocorrelation or heteroskedasticity.

Table 8: Model Diagnostic Analysis

Problem	Test	Statistic	Prob.	Outcomes
Model Specification	Ramsey RESET Test	0.5518	0.4718	Correct
Autocorrelation	Breusch-Godfrey Serial Correlation LM Test	1.3627	0.1725	Not Found
Heteroskedasticity	Breusch-Pagan-Godfrey	1.19895	0.2265	Not Found

Furthermore, figure 2 shows that the fitted lines are within the critical region lines at 5 percent level suggesting that the model is dynamically stable.

Figure 2: Stability of Model



Granger Causality Analysis

Table 9 presents the results of the Granger Causality test to examine directional relationships between Environmental Quality (EQ) and various independent variables. The test determines whether changes in one variable statistically "precede" or predict changes in another. For most variables renewable energy consumption (REC), industrialization (IND), financial development (FD), and the interaction term DIG_REC no significant causality is observed in either direction, as all p-values exceed the 0.05 threshold. This implies that these variables do not Granger cause environmental quality, nor does environmental quality Granger cause them, within the sample period. However, a notable exception is population growth (PGR) and digitalization, which significantly Granger causes environmental quality. This result indicates that past changes in population growth can be used to predict future changes in environmental quality.

Table 9: Granger Causality Estimates

Null Hypothesis:	Obs	F-Statistic	Prob.
DGI ≠ EQ	26	5.23440	0.0021
EQ ≠ DGI		0.41023	0.4091
REC ≠ EQ	26	0.28311	0.7563
EQ ≠ REC		0.49153	0.6186
IND ≠ EQ	26	0.00607	0.9940
EQ ≠ IND		0.48380	0.6231
FD ≠ EQ	26	1.66037	0.2141
EQ ≠ FD		0.79566	0.4644
PGR ≠ EQ	26	6.59464	0.0060
EQ ≠ PGR		0.73176	0.4929
DGI_REC ≠ EQ	26	0.24859	0.7822
EQ ≠ DGI_REC		0.62353	0.5457

Conclusion

This study explores the effects of digitalization and renewable energy on environmental quality in Pakistan, using time series data from 1996 to 2023. By employing solid econometric techniques, including the Augmented Dickey-Fuller (ADF) unit root test, ARDL bounds testing, and both short-run and long-run ARDL models, the study provides in depth understanding of how modern technologies and energy practices form environmental sustainability in a developing country context. The unit root test confirmed that the data consisted of a mix of I (0) and I (1) variables, making the ARDL technique appropriate for analysis. The ARDL bounds test confirmed the presence of a long-run cointegration relationship between environmental quality and the selected explanatory variables, justifying further investigation through long-run and short-run modeling.

The study found that digitalization had an adverse and significant effect on environmental degradation in the long run analysis. This suggests that digital progress, including smart technologies, data analytics, and automated systems, help to enhance the environmental situation by integrating energy efficiency, minimizing emissions, and improving environmental control. The results confirm the idea that digital change may become an effective instrument of achieving sustainable development. Environmental degradation was also greatly affected negatively by the consumption of renewable energy. This means that the more the share of clean energy sources such as solar, wind and hydropower, the more effective it will be in boosting the quality of the environment in Pakistan. The outcome is consistent with the global transforming efforts to give up the use of fossil fuels, in favor of more eco-friendly and renewable sources of energy. Industrialization however had a significant and positive impact on environmental degradation, which means that the industrial processes in the current Pakistani industry are still based on using polluting technologies and non-sustainable resources. This shows the importance of greater environmental regulation, cleaner production technologies and reforms in industrial policy to reduce the negative environmental impact of the sector (Awan & Yaseen, 1017)

It was also shown that financial development and population growth had no statistically significant effects on environmental degradation both in the short and long run. Although in theory financial development can facilitate green investments, its presence in Pakistan does not have a huge impact on the environmental performance, and it may be explained by the low level of environmental financing or absence of green policy orientation in the financial industry. On the same note, despite the fact that population growth has been found to be a challenge in environmental management, its isolated statistical insignificance indicates that its effects are indirectly influenced by other factors like consumption, urbanization and governance. The cross-product term of digitalization and renewable energy (DGI_REC) indicated that there was a significant and strong adverse relationship between environmental degradation and the long-term. It suggests a synergy effect, in which the mutual development of digital infrastructure and renewable energy has an effect on environmental outcomes greater than the effect of either of the two factors in isolation. This interaction, however, in the short run was a positive one and it may be because of transition related issues like infrastructure adaptation or energy demand during implementation. The model was proven reliable using diagnostic tests and it had no specification errors, autocorrelation or heteroskedasticity. Also, Granger causality tests revealed that population growth was the causal factor of the environmental degradation, whereas other variables did not have any direct causal impact in the short run.

In conclusion, the study highlights that digitalization and renewable energy are critical levers for improving environmental quality in Pakistan. However, challenges remain in greening the industrial sector and leveraging financial systems to support sustainability. An integrated policy framework that strengthens digital infrastructure, expands renewable energy, and encourages sustainable industrial practices is essential to achieve long-term environmental goals.

Policy Implications

The empirical impact should be placed on priority on policy action. To start with, digitalization and renewable energy systems should be expanded by the government together since their joint impact proves to have the most significant environmental benefits, and smart grids and the digital energy management should be invested in. Second, incentives, grid upgrades and expedited approvals should be used to accelerate renewable energy capacity. Third, the industrial sector requires more stringent environmental laws and cleaner technologies that contribute greatly to the degradation. Fourth, the financial institutions are supposed to be redirected to green financing instruments. Lastly, a balance between environmental pressure due to population growth needs to be achieved by smart city planning and digital efficiency indicators.

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