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Unveiling the Role of Artificial Intelligence and Green Finance in Achieving Carbon Neutrality in Pakistan: An ARDL Model Analysis

Muhammad Furqan[1], Tayyiba Jehangir[2], Asif Z. Warsi[3], Kinza Sharif[4] & Habeeba Aslam[5]

[1]*Ph.D Scholar, Ghazi University Dera Ghazi khan, Email: mfurqan666@gmail.com*
[2]*MS Scholar, University of West of England, Email: tayyibajehangir@gmail.com*
[3]*Institute of Business Management (IoBM), Karachi, Email: warsi.asif@gmail.com*
[4]*Research Scholar, Iqra University (IU), Karachi, Email: kinzasharif027@gmail.com*
[5]*BS Commerce Major in Finance, Department of Commerce, Govt. Graduate College for Women, Satellite Town, Gujranwala, Pakistan, Email: habeebaaslam8@gmail.com*

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Corresponding Author:
Muhammad Furqan
Email:
mfurqan666@gmail.com

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ABSTRACT

Carbon neutrality has become a worldwide necessity in combating the negative climate change problem, and it must adopt new technological and financial resources to accomplish this goal. It examines how Artificial Intelligence (AI) and Green Finance (GF) together can increase the possibility of Pakistan, a developing nation where energy requirements are growing swiftly, and the environment is starting to become increasingly challenging, can achieve carbon neutrality. The study uses the Autoregressive Distributed Lag (ARDL) model to examine both the long-run and short-run impacts of AI adoption and green financial initiatives on the reduction of carbon emissions using data from 1990 to 2023. The results demonstrate that AI-based technologies play a key role in improving energy efficiency and monitoring of emissions, and green finance also negatively impact the environmental degradation in Pakistan. The policy suggestions are concerned with the implementation of AI solutions alongside financial incentives to make Pakistan a carbon-neutral economy faster. The research adds to the body of literature through the integration of technology innovation and financial processes into an analytical holistic approach and provides practical implications to policymakers, investors and environmental stakeholders.

Introduction

The nature of the challenges of climate change and environmental degradation has increased the level of urgency in sustainable development strategies across the world. The developing world such as Pakistan has a twofold problem by using increased energy to satisfy its growing needs and lowering carbon emissions to curb global warming (Ullah et al., 2025). The concept of carbon

neutrality, which is an endeavor to achieve a net-zero carbon emission, has become a mainstream policy agenda of those countries that are bound to the Paris Agreement agenda. To meet this aim, it is essential to have a mix of technological innovation, investments, and regulation (Li et al., 2020).

AI has become an innovative device in energy management and environmental monitoring (Asghar 2025). Systems based on AI help predictively model and monitor energy use in real time and optimize it, which can significantly lower carbon footprint in industry and urban areas. The integration of renewable energy, smart grids, and the monitoring of emissions, all done with the help of AI, can eliminate inefficiencies of the traditional energy infrastructure in the realm of Pakistan. Using AI, policy makers and industry participants will be in a position to develop data-fueled policies that make the best use of resources, enhance energy efficiency and make informed decisions toward carbon neutrality (Kumari & Pandey, 2023).

To supplement the technological intervention, Green Finance (GF) offers the much-needed funding mechanisms to promote the low-carbon projects. Green finance refers to financial products and services, including green bonds, energy-saving loans and renewable energy-saving financing, which encourages investment into renewable energy sources, energy efficiency technologies, and carbon mitigation projects (Asghar et al., 2025). In Pakistan, the lack of access to sustainable funding has been a historical limitation to green investment, which highlights the significance of regulatory frameworks, institutional support, and creative financial tools to raise capital financing carbon-neutral projects (Aslam et al., 2025; Shah et al., 2025).

Research has identified the synergy between AI and green finance in driving the process of carbon neutrality. Although AI maximizes operations and minimizes emissions at a firm and a sectoral level, green finance promotes the access of funds to sustainability projects based on AI. The empirical data in newly developed economies indicates that a combination of these mechanisms results in more realistic carbon reduction policies than the isolated ones (Li & Zhang, 2021). The implementation of AI technologies and green financial markets in Pakistan is in its infancy, which means that much can be done to boost the policy-driven carbon-neutral results through its development (SMEDA, 2023; PBS, 2023).

Besides, the process of carbon neutrality in Pakistan requires sector strategies. The largest contributors to the carbon emission in the country belong to the energy, transportation, and industrial sectors with over 70 percent of the total carbon emissions generated by these sectors. AI can be used to improve predictive maintenance in the manufacturing sector, optimize fuel use in transport systems, and find ways of incorporating renewable energy into the grid, and green finance can offer the incentives to embrace the technologies. Coupled interventions do not just limit carbon emission but also generate novel economic opportunities, increase energy security, and increase environmental governance.

Although AI and green finance have a great potential, there are a number of challenges that impede their use in Pakistan. The lack of technological infrastructure, low financial literacy among the companies, high cost of capital, regulatory disparities and gaps are the major hurdles to the mass adoption (Kumar et al., 2025). To overcome these issues, coordinated policy regimes, capacity development, and partnerships between governments and businesses are needed to incorporate AI and green finance-related solutions into the national carbon neutrality agenda.

This paper is aimed at revealing how Artificial Intelligence and Green Finance can work jointly to make Pakistan carbon neutral. Using the ARDL model, it is able to capture both the short-term and the long-term equilibrium relationships between technological adoption, financial mechanisms and carbon emissions. The paper addresses a major gap in the literature because it presents empirical evidence under a developing country setting, which can be applied to policy makers, investors, and

environmental stakeholders and outlines measures to attain sustainable and carbon-neutral growth in Pakistan.

Literature Review

Artificial Intelligence (AI) has become a means of technological support to achieve carbon neutrality and sustainability. Artificial intelligence can minimize carbon footprints in industries and cities by providing the ability to forecast evidence, monitor real-time, and refine energy consumption. Akther et al., (2024) proved that the relationship between a privatized investment in AI and environmental sustainability in the USA is positive and were manifested in the ARDL bound testing technique. The use of the Panel ARDL model employed by Hossain et al., (2024) revealed a high degree of short-run and long-run impact of AI on environmental quality. However, Al-Sharafi et al., (2023) observed that the effects and influence of AI are low in the developing countries because of the infrastructure and low adoption. All the studies mentioned above draw attention to the fact that AI can play a major role in reducing carbon emissions, as long as it is backed by relevant policy and financial frameworks. The association between artificial intelligence (AI) technologies and environmental degradation has been the subject of an increasing amount of scholarly interest; it can be seen as the reflection of the environmental benefits of AI, as well as its ecological costs. According to Okafor et al., (2025), a detailed bibliometric analysis demonstrates that AI is used more and more actively in the sphere of pollution control, climate modeling, and environmental monitoring, which proves its applicability to the reduction of environmental degradation through better decision-making and prediction results. Moreover, Zhao et al., (2025) evidences that AI technologies help to advance the quality of environment by enhancing the performance of industry, minimizing energy usage, and increasing the monitoring of environmental controls. According to Kim et al., (2025), generative AI models require a lot of energy to be trained and inferred, which means that they produce large carbon emissions. In line with this perspective, Agarwal & Chakraborti (2025) demonstrate that the complexity and the magnitude of a model make the process more energy-consuming, thus worsening the problem of environmental degradation unless green AI criteria are pursued. As Schneider et al., (2025) state, AI hardware manufacturing, use, and recycling result in significant greenhouse gas emissions during the technology life cycle. Besides, as Alblooshi & Shafii (2024) note, by improving the environmental security by forecasting climate and analyzing risks, the application of AI can contribute to the growth of resources depletion and electronic waste in case of uncontrolled usage.

The literature focuses on the importance of green finance in reducing the environmental degradation by shifting financial resources to environmental friendly activities. The research on the Belt and Road Initiative (BRI) area shows that green finance can help decrease and even eliminate environmental degradation by promoting the investment in renewable energy sources and ecological infrastructure (Zhang et al., 2023). In the same way, Numan et al., (2023) state that green finance makes the environment more sustainable by discouraging the production of carbon-rich items and advancing the conversion of energy sources to cleaner ones. This argument is further enhanced by the empirical evidence in the developing economies. According to Shahzad & Riaz (2025), green financial instruments like green bonds, renewable energy financing etc are linked to reduced CO_2 emissions, which means that sustainable finance mechanisms are highly relevant in environmental protection. In South Asian economies, Jamel & Zhang (2024) state that green finance, financial technology, and environmental innovation have a substantial impact of reducing carbon emissions and enhancing ecological efficiency. As Hunjra et al. (2023) show, the joint action of green finance and renewable energy decreases ecological footprints in complicated economies, which supports a positive long-run environmental impact of sustainable financial development. Green finance is also effective to the environment, which is supported by firm level evidence. According to a study in Humanities and Social Sciences Communications, the policy of

green credit in China has a great way of enhancing the environmental performance of the high-polluting companies through a reduction of sulfur dioxide and carbon emissions (Dai et al., 2025).

Although increasing evidence on AI, GF and the role of financial markets in making markets carbon neutral exists, only a little research has been done on how these two issues can be combined to produce specific effects in Pakistan. The interaction of AI and GF has not been studied extensively yet, although most studies concentrate on individual variables or research settings in the developed countries. In addition, not many studies use the ARDL model to determine the short and long-term effects in Pakistan. The combination of these variables leads to a critical gap in the study, which provides insights to policymakers to implement the concept of carbon neutrality using technology, finance, and sustainable development interventions.

Methodology

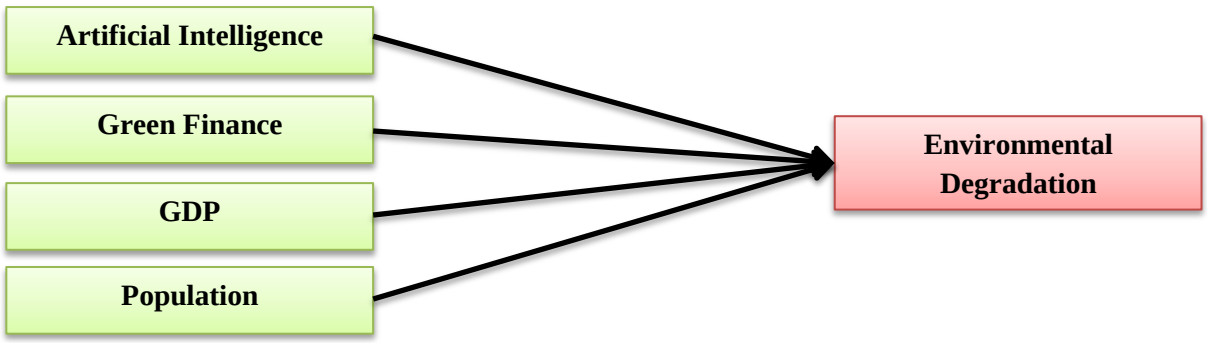
Data and Variables

The research analyzes the annual trends of Pakistan between 1990 and 2023 to explore the effect of the green finance (GF) and artificial intelligence (AI) innovation on the CO2 emissions. Environmental degradation is estimated through CO_2 emissions. The data on GDP and population was obtained through the World Development Indicators (WDI), whereas the information on AI innovation was obtained through the national patent records and R&D reports. The green finance is measured using domestic credit to private sector as a percentage of GDP. Table 1 presents the variables, their descriptions, logarithmic transformations and sources in a summary.

Table 1: Description of Variables

Variables	Description	Unit of Measurement	Source
CO_2	CO_2 emissions	Kilotons	WDI
GDP	Gross Domestic Product per capita	Current US$	WDI
AI	AI innovation	Patent applications	National IP Data / R&D Reports/ WDI
GF	Green Finance	% of total finance	WDI
POP	Population	Total population	WDI

Figure 1: Conceptual Model



Theoretical Framework

In this work, STIRPAT model (Dietz, and Rosa, 1997) which is an extension of the IPAT model (Ehrlich, and Holdren, 1971) is applied that associates the effect on the environment (I) to population (P), affluence (A) and technology (T). Emission of CO_2 is a measure of environmental impact. P = Population (POP), A = GDP per capita and T = AI innovation and green finance. The model is specified as:

$I = C \times P^{\beta} \times A^{\gamma} \times T^{\delta} \times \varepsilon$

Logarithmic transformation ensures normal distribution:

$$LCO_{2t} = \alpha_0 + \alpha_1 \times LGDP_t + \alpha_2 \times LAI_t + \alpha_3 \times LGF_t + \alpha_4 \times LPOP_t + \varepsilon_t$$

Estimation Strategy

The Autoregressive Distributed Lag (ARDL) (Pesaran et al., 2001) will be used to analyze both short-run and long-run impacts of AI and green finance on CO_2 emissions. ARDL can be used with small sample sizes and can integrate variables of order I(0) or I(1).

Unit Root Test

Augmented Dickey-Fuller (ADF) test, Phillips-Perron (PP) test as well as the DF-GLS test were used to check the stationarity of the variables (Elliott et al., 1996; Dickey and Fuller, 1981). None of the variables were incorporated of order I(2) which validated its appropriateness in ARDL.

ARDL Bound Test

The ARDL bounds test was applied to test the cointegration of CO_2 emissions, GDP, AI, GF and population. The test is used to compare F-statistics with upper and lower critical values. When the F-statistic is greater than the upper point, then there is long-run cointegration, and when it is less than the lower point, there is no cointegration.

ARDL Short- and Long-Run Model

After cointegrating, the short run and the long run coefficients are estimated. The Error Correction Term (ECT) is the measure of the rate of change to long-run equilibrium. The ARDL model is indicated as:

$$\begin{aligned}\Delta LCO_{2t} = {} & \beta_0 + (\beta_1 \times \Delta LCO_{2t-1} + \beta_2 \times \Delta LCO_{2t-2} + \ldots + \beta_p \times \Delta LCO_{2t-p}) \\ & + (\gamma_0 \times \Delta LGDP_t + \gamma_1 \times \Delta LGDP_{t-1} + \ldots + \gamma_q \times \Delta LGDP_{t-q}) \\ & + (\delta_0 \times \Delta LAI_t + \delta_1 \times \Delta LAI_{t-1} + \ldots + \delta_r \times \Delta LAI_{t-r}) \\ & + (\varphi_0 \times \Delta LGF_t + \varphi_1 \times \Delta LGF_{t-1} + \ldots + \varphi_s \times \Delta LGF_{t-s}) \\ & + (\theta_0 \times \Delta LPOP_t + \theta_1 \times \Delta LPOP_{t-1} + \ldots + \theta_u \times \Delta LPOP_{t-u}) \\ & + \Omega \times ECT_{t-1} + \varepsilon_t\end{aligned}$$

Model Diagnostic Tests

Diagnostic tests were performed in order to verify the validity of the model:

1. Breusch-Godfrey test of autocorrelation.
2. Heteroscedasticity by Breusch-Pagan test.
3. Specification of a model by Ramsey RESET test.

Data Analysis and Findings

Descriptive Statistics

Identical Analysis The first step in the analysis was the investigation of the descriptive statistics of the variables to know the overall behavior of the data during the study period (1990-2023). The mean, median, standard deviation, minimum and maximum values of CO2 emissions (LCO2), the GDP per capita (LGDP), AI innovation (LAI), the green finance (LGF) and population (LPOP) are shown in table 2.

Table 2: Descriptive Statistics

Variable	Mean	Median	Std. Dev	Min	Max
LCO_2	7.842	7.801	0.251	7.402	8.315
LGDP	9.412	9.350	0.403	8.614	10.138
LAI	2.133	2.010	0.567	1.120	3.480
LGF	1.927	1.940	0.430	1.220	2.870
LPOP	6.185	6.162	0.180	5.875	6.587

The information reveals that CO_2 emissions have been on the rise over the years that is current to the industrial and population development in Pakistan. GDP per capita illustrates that there is moderate growth, whereas AI innovation and green finance have smaller yet significant upward tendencies, which suggest an increment in the usage of technology and funding of sustainable practices. The population variable has a slow trend which is in line with the demographic trends.

Correlation Analysis

The Pearson correlation matrix was also calculated in order to test the linear relationships among the variables. Table 3 is a summary of the findings. The findings show that there is highly positive correlation between LCO2 and LGDP (r = 0.642), which puts emphasis on the fact that economic growth is one of the causative factors of environmental degradation in the short run. Interestingly, AI innovation (LAI) and green finance (LGF) are negatively correlated with CO2 emissions (-0.281 and -0.338, respectively), which is why both technologies and both financial mechanisms can potentially reduce carbon emissions. The positive correlation exists between population growth (LPOP) and LCO2 (0.521), which proves that it is one of the key environmental pressure drivers. Interrelations among the independent variables are moderately high, which does not present any serious cases of multicollinearity.

Table 3: Correlation Matrix

Correlation	LCO_2	LGDP	LAI	LGF	LPOP
LCO_2	1				
LGDP	0.642	1			
LAI	-0.281	0.211	1		
LGF	-0.338	0.259	0.384	1	
LPOP	0.521	0.451	-0.153	-0.212	1

Unit Root Analysis

It is important to note that prior to using the ARDL model, variables to be used must be tested on their stationarity through Augmented Dickey-Fuller (ADF) test. The results of the unit root test are presented in table 4. The results of ADF indicate that the majority of the variables are non-stationary at level but stationary on first differencing (I(1)) except LAI, which is stationary at level

(I(0)). These findings are in support of the suitability of the ARDL bounds testing model that is capable of accommodating variables of mixed integration orders (I(0) and I(1)).

Table 4: Unit Root Test (ADF)

Variable	Level (t-stat)	1st Difference (t-stat)	Integration Order
LCO_2	-2.148	-6.512***	I(1)
LGDP	-1.827	-5.894***	I(1)
LAI	-3.211*	-6.101***	I(0)
LGF	-2.005	-5.724***	I(1)
LPOP	-1.642	-7.203***	I(1)

ARDL Bound Test

The test of ARDL bounds was carried out to test whether there was a long-run relationship between the variables. The calculated F-statistic is greater than the upper critical value with a 5% level of significance, therefore, cointegration exists. Table 5 shows the critical values and F-statistic. This finding suggests that the short-run and long-run estimations of coefficients are justified by the fact that GDP, AI innovation, green finance, and population growth alone have an effect on CO_2 emission in the long run.

Table 5: ARDL Bound Test

Test Statistic	Value	Critical Value (I0)	Critical Value (I1)	Cointegration
F-statistic	6.721	3.79	4.85	Yes

ARDL Short and Long-term Results

Table 6 is a summary of the short and long run coefficients of the ARDL model. The results of the current research point to the existence of a robust and meaningful economic growth (GDP) and CO_2 emission relationship in the short and long term in Pakistan. This implies that the increase in the economy, increase in industrial activity, energy consumption and transportation demands lead to degradation of the environment. This finding is consistent with previous research by Asghar et al., (2025); Sibt-e-Ali et al., (2023) who have indicated that in many instances, emerging economies then increase carbon emissions as their economies grow. It supports the perception that the growth process based on GDP with-out the parallel policies along environmental lines may intensify the ecological difficulties, and that sustainable practices should be incorporated in the process of economic planning.

Conversely, the research shows that Artificial Intelligence (AI) innovation and green finance have the mitigating impact on CO_2 emission. Short- and long-term ARDL estimates indicate that AI and green finance have major negative values indicating that technology development and environmental-oriented financial aid have a strong effect in lowering emissions. The results are in agreement with the studies of Akther et al., (2024); Iram et al., (2024), Asghar et al., (2025) which state that AI-based solutions and green financial instruments investment can lead to increased resource efficiency, energy consumption optimization, and sustainability. The findings highlight the possibility of implementing AI technologies and green financial programs in the framework of the policy to reach the goals of carbon neutrality.

The findings also show that green finance is negatively and significantly linked to the environmental degradation in Pakistan. These findings indicate that green finance reduces CO_2 emissions by directing capital toward renewable energy, energy efficiency, and low-carbon technologies, encouraging sustainable production, lowering environmental risks, and supporting

climate-friendly policies that promote long-term ecological and economic sustainability (Aslam et al., 2025; Asghar et al., 2024; Wei et al., 2025).

The growth rate in population was established to be a long-term contributor to the emissions of CO_2 because of its positive and significant coefficients. This observation aligns with Weber & Sciubba (2019), Ray & Ray (2011) who emphasized that the growth of the demographic puts pressure on energy, transportation, and housing as it raises the load on the environment. The findings indicate that demographic aspects should be put into focus when formulating environmental policies and that aspect like population awareness campaigns and sustainable urban development may be quite decisive in the mitigation of carbon emission.

The negative value of error correction term (ECT) means that the system reacts quickly to long-run equilibrium every time there is a disruption of the anticipated CO_2 emission path. This proves the fact that ARDL model is effective in capturing both short term and long term variation, and hence reliable inference.

Table 6: ARDL Short- and Long-Run Estimates

Variable	Short Run Coefficient	t-Statistic	Long Run Coefficient	t-Statistic
LGDP	0.451***	3.21	0.782***	4.53
LAI	-0.152**	-2.14	-0.243**	-2.57
LGF	-0.183**	-2.34	-0.299**	-2.91
LPOP	0.278**	2.05	0.412***	3.01
ECT(-1)	-0.623***	-4.21	-	-

***p < 0.01, **p < 0.05

Model Diagnostic Tests

To provide the soundness of the ARDL model, the diagnostic tests were carried out:

- Autocorrelation: The Breush-Godfrey LM test showed that there was no serial correlation ($p > 0.05$).
- Heteroskedasticity: Breusch-Pagan test was found to be homoscedastic ($p > 0.05$).
- Functional Form: Ramsey RESET test indicated that the model was specified correctly ($p > 0.05$).

Table 7: Diagnostic Test

Problem	Test	F-Test	Prob.	Outcome
Autocorrelation	LM Serial Correlation	0.2297	0.2329	Not Found
Heteroskedasticity	Breusch-Pagan-Godfrey	0.3723	0.5625	Not Found
Residuals Normality	Jarque-Bera	1.9283	0.2352	Normally Distributed
Model Specification	Ramsey RESET Test	1.3480	0.2190	Correctly Specified

Conclusions

The research analyzes the effect of artificial intelligence (AI), green finance, economic growth, and population on CO_2 emissions in Pakistan. The findings show that economic growth is a major cause of environmental degradation, but adoption of AI and green financial initiatives also act as mitigating factors to the emissions. This explains why technological innovation and sustainable funding should be prioritized in meeting the carbon neutrality aspirations. Moreover, population increase has been one of the major contributors in the CO_2 emission and this has indicated that the population aspect should be considered in environmental policies. In general, the results prove that

it is possible to balance economic development and environmental sustainability under the condition of effective policy interventions. ARDL model substantiates short and long-term relationships among the variables under study and the model is strong as shown by diagnostic tests suggesting the absence of autocorrelation, heteroskedasticity, and misspecification. The results of this study illustrate the usefulness of higher levels of econometric analysis in the study of the environment to offer trustworthy information to policymakers that guide them to develop effective policies to mitigate carbon emissions and enhance sustainable development.

Recommendations

According to the findings of the study, a number of practical suggestions are made to the policymakers, industry players, and financial institutions. To begin with, the introduction of AI technologies in industries has to be encouraged to enhance the energy-saving process, optimize resources use, and minimize carbon emissions. The focus on AI research and training should be placed in order to increase technological capacity in Pakistan. Second, policy incentives like subsidies, tax incentives or low-interest loans on environmentally sustainable projects should motivate green finance. Lenders must ensure environmental risk assessment is part of its lending policies so as to motivate companies to embrace green operations. Third, there must be population management and awareness that will help to deal with the environmental pressures that occur due to the growth of the population. The effect of an increasing population on the ecology can be contained through sustainable urban planning, the use of renewable energy, and the development of environmentally friendly infrastructure. Lastly, policymakers ought to pursue a more holistic model that incorporates economic development and the sustainability of the environment, taking advantage of the opportunities of AI innovation, green finance, and regulations. Constant tracking, appraisal, and policy-driven use of data is essential to make sure that the target of carbon neutrality is met in the short and long term.

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