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Toward Environmental Sustainability in Pakistan: The Role of Green Technological Innovation, Green Finance, and Financial Development

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Abstract

This study examines how green technology innovation (GTI), green finance (GF), gross domestic product (GDP), and financial development (FD) affect environmental quality in Pakistan using annual data from 1990 to 2024. Autoregressive Distributed Lag (ARDL) and Nonlinear ARDL (NARDL) models estimate symmetric and asymmetric long-run relationships for five environmental indicators; carbon dioxide emissions, ecological footprint, methane emissions, nitrous oxide emissions, and deforestation. ARDL estimates show that GTI, GF, and FD are negatively associated with environmental degradation, whereas GDP is positively associated with it, consistent with the rising segment of the environmental Kuznets curve. NARDL results confirm asymmetry in the GTI–environment nexus; positive shocks to GTI reduce emissions, while negative shocks increase them. Policymakers should scale up public and private investment in green technology, expand green financing instruments such as green bonds and concessional credit, and tie financial-sector growth to environmental disclosure standards so that economic expansion does not raise emissions.

Keywords: Green technological innovation, green finance, financial development, carbon emissions, deforestation.

1. Introduction

Global warming and climate change are driving environmental degradation and creating urgent sustainability concerns (Farooq et al., 2023; Yan et al., 2023; Zhou et al., 2024). Over the past three decades, greenhouse gas emissions have risen relentlessly, jeopardizing ecosystems, human survival, and future sustainability (Han et al., 2023; Khan et al., 2026). Because this escalation is driven primarily by human-induced carbon emissions, nations increasingly agree on the need to reduce emissions and pursue sustainable development

(Chandio et al., 2025; Shi et al., 2026). The central challenge is to achieve this without impeding development (Khan et al., 2020).

This is evident in Pakistan. It accounts for approximately 0.8% of global emissions, but is more vulnerable to climate change impacts; environmental issues are estimated to impact GDP by around 6% per year (Majeed et al., 2020). Over 60 percent of its power is produced by thermal resources and its emissions of the particulate substances of nitrogen oxides and carbon dioxide are on the rise, causing air quality to quickly deteriorate. CO_2 makes up 54% of Pakistan's greenhouse gas (GHG) emissions, followed by methane (36%), nitrous oxide (9%), carbon monoxide (0.75%) and fluorinated gases (c. 0.3%). The International Energy Agency breaks down CO_2 emissions by sector as follows: electricity 31%, transport 28%, manufacturing 27%, other sources 13% and the energy sector 1%. The size, age, engine technology, fuel quality, and fuel consumption of the vehicles are some important factors affecting transport emissions (Abas et al., 2017; Tanveer et al., 2023). This emphasis on energy, transport and manufacturing suggests that the organization and financing of production is an important determinant of mitigation.

This study can be justified by the conflicts between development and ecology. The economies have developed at an unprecedented level largely owing to the development of trade, financial innovations, and technological advancements (Chandio et al., 2023; Yu et al., 2023; Hashemizadeh et al., 2023). But as countries grow, pollution often increases, since the sectors which drive economic activity; manufacturing, energy extraction and the petroleum sector are also significant contributors of CO_2 (Suhrab et al., 2023). Increased energy demand and economic growth are therefore the leading pressures on ecosystems, as growth has improved the living standard but has also impacted ecosystems and human health (Akram et al., 2023; Farooq et al., 2023). Reducing CO_2 emissions is therefore a challenge for a country to do so without reducing its national income or the welfare of the society and unchecked pollution poses a threat for long-term growth (Awan & Azam, 2022). The significance of innovation in meeting these goals has led to innovation being a prominent feature in climate policy debates (Dauda et al., 2019).

Two in particular are relevant. First, technological improvement is flexible in terms of input composition and energy efficiency, which can reduce emissions (Khan et al., 2020; Huang et al., 2026), and the dynamic relationship between technological improvement and CO_2 emissions is complicated for countries that have introduced new production methods (Li, 2026). But gains in efficiency can also encourage industrial growth, which can increase levels of energy and raw materials consumption and cause an environmental set off against the gains (Wenlong et al., 2023). Second, there are multiple pathways by which financial development affects emissions. The financial sector can foster environmental development through its ability to fund environmental R&D, facilitate access to cleaner technologies for firms, supply low-cost financing for environmentally innovative projects, and ensure that firms meet ecological standards (Majeed et al., 2020; Javaid et al., 2023; Horobet et al.,

2025). Concurrently, it can increase emissions: on the demand side, increased access to credit can lead to an increase in the number of vehicles bought by domestic households or in the number of energy-intensive durables purchased by domestic firms, and on the supply side, increased access to credit can lead to an expansion of industrial capacity via the purchase of energy-intensive machinery by domestic firms. A more targeted tool is green finance. It channeled money into sustainable products, green transitions and energy efficiency schemes, and made business goals eco-friendly, as opposed to traditional finance (Gan & Voda, 2023; Iqbal et al., 2025). The Central Bank and financial regulators have started to give importance to climate risks in the investment sphere because climate risk is becoming an imminent threat to investments (Nawaz et al., 2021; Zhang et al., 2024).

This is a tension that doesn't resolve in these strands. Technological innovation and financial development can have either a positive or a negative impact on emissions, and their overall environmental impact is uncertain. The impact of technological innovation on the environment, as seen from the existing evidence, is influenced by the economic and institutional conditions of a country, and has a higher impact in countries with a stronger green finance and financial development. Based on the existing evidence, the environmental effect of technological innovation depends on the economic and institutional conditions in a country, and is greater in countries with greater green finance and financial development (Qamruzzaman & Jianguo, 2020; Kumar & Wu, 2025). This role of conditioning remains little explored in Pakistan which is a thermal-based and emissions-intensive economy, highly vulnerable to climate risks.

The study has three aspects. It provides country-specific evidence for an economy where emissions are localized in electricity, transport and manufacturing, but which makes a small contribution to global emissions, meaning that mitigation needs to be balanced with development needs. It addresses the question of whether green finance and financial development build up or weaken the emission-reducing potential of green innovation, instead of considering these factors individually. It also offers empirical grounds for coordinating technology, financial and environmental policies.

This study is a contribution to the literature in four ways. Firstly, it offers country-specific evidence for Pakistan and instead of environmental proxy measures, it uses complementary measures to evaluate environmental quality such as CO_2 emission, methane, nitrous oxide, ecological footprint, and deforestation. Second, it also explores the yet unsettled issue of the linear or nonlinear impact of technological innovation on the environment, by providing an estimate of the asymmetric environmental impact of green technological innovation. Third, it contains both linear and nonlinear estimation frameworks, leading to a more reliable estimation of how interactions between green technological innovation, green finance, GDP, and financial development are related than either linear or nonlinear estimation alone. Lastly, the results provide valuable policy and regulatory implications for Pakistan to achieve long-term environmental sustainability.

The study is organized as follows: Section 2 presents the literature review. The methodology used, such as data interpretation and variable measurements, is outlined in section 3. Section 4 delves into the results and offers a brief discussion. Lastly, the "Conclusion and Policy Implications" section captures the findings and recommends related policies on the findings.

2. Literature Review

2.1 Green Technological Innovation and Environment

Technological innovation has been seen since ages as a major contributor to the economic development. Major technological change must occur to produce economic and financial benefits, according to Semieniuk et al. (2021) who have adapted Schumpeter's theory of innovation. The environmental significance of innovation arises from the impact of growth on pollution. An increase in production increases energy consumption, thereby straining the environment. A "technique effect" can compensate for this scale effect by using innovations that are environmentally-friendly. They help to increase energy efficiency, enable cleaner production practices, and minimize harmful emissions (Cai & Li, 2018; Petrović & Lobanov, 2020). In this context, GTI could be a tool that helps to reconcile growth with environmental goals in economies.

This is generally corroborated by the empirical literature. This negative correlation between GTI and environmental degradation seems to hold true in very different contexts, indicating that this finding is applicable to a range of contexts beyond the specific context in which it was discovered. So far, the studies conducted in single countries have reported that the adoption of GTI is associated with reduced CO2 emissions in China (Khan et al., 2020), Malaysia (Ali et al., 2020), Turkey (Shan et al., 2021) and the United States (Razzaq et al., 2023). The Asian economies (Bakhsh et al., 2021; Wenlong et al., 2023), the OECD countries (Jianguo et al., 2022) and a larger sample of economies (Rafique et al., 2020) report similar results for panel studies. The finding also applies for the FMOLS, bootstrap ARDL, quantile ARDL, AMG and GMM-type panel estimators. It also applies to environmental indicators. As revealed by Ozkan et al. (2023), the benefits of GTI are not only limited to carbon emissions, but also to the broader pressure of resources in Turkey.

This is no blanket agreement. Du et al. (2019) find that the emissions-reducing impact of GTI is sensitive to economic development, being only substantial after reaching a certain income level, based on the available data for 71 economies between 1996 and 2012. This means the absorptive capacity and the structural properties of the economy are important for the environmental return of green innovation. The curve is not linear and is supported by evidence of the income-emissions relationship.

The literature also is generally agreed on the scale drivers for degradation. Economic growth raises emissions in almost every study reviewed (Rafique et al., 2020; Khan et al., 2020; Shan et al., 2021; Bakhsh et al., 2021; Ozkan et al., 2023; Razzaq et al., 2023). There

is also a positive pressure from energy consumption, population, urbanisation and industry share, with similar impacts to each other (Du et al., 2019; Rafique et al., 2020; Shan et al., 2021; Ozkan et al., 2023). Conversely, renewable energy can play a complementary role to GTI to help lower emissions (Khan et al., 2020; Shan et al., 2021). Altogether, the findings indicate that the effects of growth and energy use are offset by GTI and renewable energy.

Cross-country panel studies, on the contrary, average effects over economies which are very different with respect to income levels, energy structure and capacity of institutions, and thus can mask country-specific situations. Studies specifically on Pakistan offer more tangible evidence. Based on the ARDL model for the period 1990–2020, Lin and Ullah (2023) conclude that green innovation and green growth have a negative effect on CO2 emissions, while ICT has a positive impact. If the same method is used in the same timeframe by Ali et al. (2025), they also find that growth and green innovation reduce and increase emissions respectively. They also discover that the impact of green energy use is not firm across specifications, and that technological innovation is only important when combined with green innovation and green energy. The reason for such results is the continued consumption of fossil fuel resources in Pakistan and the slow pace of the green patenting process in the country, they believe.

2.2 Financial Development and Environment

The environmental Kuznets curve (EKC) proposed by Grossman and Krueger (1991, 1995) suggests that environmental degradation rises in the early stages of development and declines once income reaches a certain level. Later studies extended this nonlinear reasoning to financial development, which can influence CO2 emissions in two opposing ways. On the one hand, easier access to credit expands production, consumption and energy-intensive investment, raising emissions. On the other hand, financial development can fund technological advances that make production cleaner. Hao et al. (2016) support the second channel, showing that technological progress enabled by financial development lowers CO2 emission intensity. Which of these effects dominates depends on the characteristics of each economy. Zilibotti (1994) and Rioja and Valev (2004) show that the links between financial development, technological progress and growth vary with the level of economic development. The environmental effect of financial development should therefore be expected to differ across countries.

Although theory allows for either outcome, most empirical studies find that financial development increases environmental degradation. Ahmad et al. (2020) report this result for 90 Belt and Road countries, and Lv and Li (2021) confirm it for 97 countries over 2000–2014. The finding holds at the regional level as well. Javaid et al. (2023), using CS-ARDL for 13 East and South Asian economies over 1995–2021, find that financial development and economic growth both raise emissions. Country-level evidence points the same way. Majeed et al. (2020) show that financial development, energy consumption and economic growth harm environmental quality in Pakistan over 1972–2018. The effect is not limited

to developing economies either, since Du et al. (2019) find that financial development raises emissions in the G-7. Du et al. (2019) and Majeed et al. (2020) both use the NARDL approach to test for asymmetry. Du et al. (2019) show that both positive and negative shocks to financial development increase emissions. Overall, this body of work suggests that in many economies the scale effect of financial expansion outweighs its technological benefits.

However, the evidence is not entirely one-sided. For the GCC region over 1995–2019, Islam et al. (2023) apply a PMG-NARDL model and find that financial development and information and communication technology improve environmental quality, while energy consumption worsens it. Read alongside the intensity reductions reported by Hao et al. (2016), this result indicates that financial development can benefit the environment when funds are directed toward cleaner technologies. The finance–environment relationship therefore appears to depend on context rather than being fixed in sign.

These studies also agree broadly on the other factors that shape emissions. Economic growth, energy consumption and urbanisation consistently increase emissions (Ahmad et al., 2020; Majeed et al., 2020; Lv & Li, 2021; Javaid et al., 2023; Islam et al., 2023). Human capital consistently reduces them, in both the G-7 (Du et al., 2019) and East and South Asia (Javaid et al., 2023), which points to the role of skills in adopting cleaner production. In Belt and Road countries, foreign direct investment and trade are also associated with lower emissions (Ahmad et al., 2020). The effect of renewable energy appears asymmetric, with positive and negative shocks influencing emissions differently (Du et al., 2019).

2.3 Gross Domestic Product and Environment

Grossman and Krueger (1991, 1995) proposed the environmental Kuznets curve (EKC), an inverted U-shaped relationship between income and pollution. Pollution is low in the pre-industrial stage and rises during industrialization as production and energy demand expand. Beyond an income threshold it declines, as economies shift toward services, adopt cleaner technologies and demand better environmental quality. There are few studies that test the entire curve. The positive GDP and negative GDP2 coefficients of the inverted U-shape verified by Aslam et al. (2021) for China support the inverted U-shape. The majority of the others depict income in linear form only. The results of these studies show a positive relationship between income and emissions in cross-country panels (Muhammad, 2019; Kahia et al., 2019; Leitão & Lorente, 2020; Adedoyin et al., 2020; Sikder et al., 2022) and in single countries (Mahmood et al., 2019; Khan et al., 2020; Zubair et al., 2020). This implies that there are still many economies that are on the ascending side of the curve.

Also, the energy composition and structural change. Non-renewable energy and nuclear power cause emissions (Mahmood et al., 2019; Adedoyin et al., 2020) while renewable energy decreases them (Kahia et al., 2019; Leitão & Lorente, 2020; Suhrab et al., 2023).

Environmental stress factors are related to industrial activities, urbanization and density of population (Aslam et al., 2021; Sikder et al., 2022).

There is conflicting evidence on external and financial factors. Some studies have shown a reduction in emissions in the case of trade (Kahia et al., 2019; Leitão & Lorente, 2020); in the case of China and Pakistan, the results have indicated an increase in emissions (Aslam et al., 2021; Suhrab et al., 2023). Kahia et al. (2019) argued that FDI contribute a reduction in emissions while Nigeria argued that FDI contribute an increment in emissions as proposed by Zubair et al. (2020). The negative association of financial development with emissions is found in 68 countries (Muhammad, 2019) whereas the positive association is found in Pakistan (Suhrab et al., 2023). This inequality is likely related to income inequality and industrialization and energy supply.

2.4 Green Finance and Environment

Green finance directs capital toward renewable energy, clean technologies and low-carbon projects, and is therefore expected to reduce emissions. Most empirical studies support this expectation. The negative relationship between green finance and the CO2 emissions is confirmed for various estimation methodologies, such as VECM, OLS and threshold models in China (Ren et al., 2020; Gan & Voda, 2023; Hu et al., 2023; Li & Fan, 2023). Cross-country evidence sheds the same light, as the results for the N-11 economies (Nawaz et al., 2021), the BRI countries (Chin et al., 2022), the G-20 (Zhang et al., 2022), OECD countries (Wang et al., 2023) and Asian economies (Sun, 2023) confirm.

The studies also show how the Green Finance impact environment. It is found to have a synergic effect with non-fossil and renewable energy (Ren et al., 2020; Zhang et al., 2022; Sun, 2023) and technological innovation (Zhang et al., 2024; Li & Fan, 2023) and green fiscal policy (Hu et al., 2023). This indicates that the contribution of green finance to emissions abatement is primarily through promoting the shift to clean energy and technology, which is supported by the empirical results that renewable energy is associated with positive environmental effects, while non-renewable energy is linked to negative environmental effects (Lu et al., 2023; Yan et al., 2023). The evidence is not entirely consistent, however. However, Ran et al. (2023) conclude that green finance led to an increase in CO2 emissions in China, and this factor could reduce its effectiveness depending on the way green finance is allocated and tracked.

Results on the other determinants are less consistent. However, in most studies, emissions are found to increase with economic growth (Zhang et al., 2022; Lu et al., 2023; Sun, 2023; Wang et al., 2023; Yan et al., 2023), while urbanization and industrialization activities increase environmental pressure in China (Gan & Voda, 2022; Li & Fan, 2023). FDI has positive environmental effects in China (Li & Fan, 2023; Ran et al., 2023) but negative effects in the G-20 (Zhang et al., 2022). Exports lead to a decrease in emissions (Lu et al., 2023; Wang et al., 2023), while OECD countries are expected to see an increase in emissions from imports, but a decrease in industrialized economies (Lu et al., 2023; Wang et al., 2023). A more appropriate indicator is provided by evidence from Pakistan where

the green finance market is in its early stages. Based on RALS-EG cointegration and ARDL model, Ali et al. (2024) conclude that green finance and human capital have negative short and long-run impacts on CO2 emissions in the short and long runs, respectively, while economic growth has positive long-run effects on CO2 emissions. It indicates that green finance is not only able to help emission reduction in the face of small green finance sector and restricted fiscal policy, but also can promote emission reduction in the face of limited green finance market scale.

3. Research Data and Methodology

In this study, data have been used for Pakistan from 1990 to 2024. Table 1 provides details on all variables used, their units of measure and sources.

Table 1: Variables Description

Variables	Symbol	Measurement	Data Source
Carbon emission	CO_2	CO_2 emissions (Total) (mt)	WDI
Ecological footprint	E.F.	Ecological footprint (gha total)	GFN
Methane	CH4	Methane emissions total (MT of CO2 equivalent)	WDI
Nitrous oxide	N_2O	Nitrous oxide emissions (total)	WDI
Deforestation	DEF	Forest area (% of land area)	WDI
Green technological innovation	GTI	Patent applications, residents	WDI
Financial Development	FD	Domestic credit to private sector (% of GDP)	WDI
Green finance	GF	Renewable energy consumption (% of total final energy consumption)	WDI
Economic Growth	GDP	GDP per capita growth (annual %)	WDI

3.1 Econometric Strategy

Autoregressive Distributed Lag (ARDL) bounds test is used in this study, which allows variables of order I(1) or I(0) with small sample analyses. The tests used to check the stationarity are Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) tests. Cointegration is done by applying the bounds test F-statistic and then, long-run coefficients are calculated along with the Error Correction Model (ECM) and diagnostic tests for serial correlation, heteroscedasticity and parameter stability.

This study also uses the Nonlinear ARDL (NARDL) model of Shin et al. (2014), which breaks the variables in the model into positive and negative partial sums, to detect nonlinearities. It is a flexible and robust method for simultaneously estimating asymmetric short- and long-run relationships in a single cointegrating equation, which is more difficult for conventional symmetric estimators (Han et al., 2023).

3.2 Econometric Model

The general form of the model is as given under:

$$ENV = f(GTI, FD, GF, GDP) \quad (1)$$

Where ENV is dependent variable with proxies, CO_2 emission, ecological footprint, Ch_4, N_2O and deforestation. GF is green finance which is proxies by renewable energy consumption as a percentage of total final energy consumption. We chose this proxy for three reasons. First, green finance is meant to channel funds toward low-carbon and renewable energy projects, so the renewable share of energy use captures the real-economy result of that financing. Second, it is available consistently for Pakistan across the whole sample, unlike direct financial measures. Third, it has been used as a proxy for green finance and green investment in earlier empirical studies (Nawaz et al., 2021; Qadri et al., 2023). GTI is the green technological innovation, FD is financial development, and GDP is gross domestic product. The econometric equation for variables and linear and nonlinear ARDL equations are as follows:

$$ENV_t = \xi_5 + \xi_6 GTI_t + \xi_7 FD_t + \xi_8 GF_t + \xi_9 GDP_t + \mu_t \quad (2)$$

Where $\zeta(5\ldots9)$ denote the estimators for CO_2 emissions,CH_4, N_2O, DEF and ecological footprints from G.F., GTIN, F.D., and GDP.

$$\Delta ENV_t = \xi_4 + \sum_{c=1}^{w} \xi_{5i} \Delta ENV_{t-1} + \sum_{c=0}^{w1} \xi_{6i} \Delta GTI_{t-i} + \sum_{c=0}^{w2} \xi_{7i} \Delta FD_{t-i} + \sum_{c=0}^{w3} \xi_{8i} \Delta GF_{t-i} + \sum_{c=0}^{w4} \xi_{9i} \Delta GDP_{t-i}$$
$$+ \vartheta_5 ENV_{t-1} + \vartheta_6 GTI_{t-1} + \vartheta_7 FD_{t-1} + \vartheta_8 GF_{t-1} + \vartheta_9 GDP_{t-1} + \mu_t \quad (3)$$

$$\Delta ENV_t = \xi_4 + \sum_{c=1}^{w} \xi_{5i} \Delta ENV_{t-1} + \sum_{c=0}^{w1} \xi_{6i} \Delta GTI^{+}{}_{t-i} + \sum_{c=0}^{w1} \xi_{6.1i} \Delta GTI^{-}{}_{t-i} + \sum_{c=0}^{w2} \xi_{7i} \Delta FD_{t-i} + \sum_{c=0}^{w3} \xi_{8i} \Delta GF_{t-i} + \sum_{c=0}^{w4} \xi_{9i} \Delta GDP_{t-i}$$
$$+ \vartheta_5 ENV_{t-1} + \vartheta_6 GTI_{t-1} + \vartheta_7 FD_{t-1} + \vartheta_8 GF_{t-1} + \vartheta_9 GDP_{t-1} + \mu_t \quad (4)$$

Estimation of the ECM Model

$$\Delta ENV_t = \xi_0 + \sum_{c=1}^{w} \xi_{1i} \Delta ENV_{t-1} + \sum_{c=0}^{w1} \xi_{2i} \Delta GTI_{t-i} + \sum_{c=0}^{w2} \xi_{3i} \Delta FD_{t-i} + \sum_{c=0}^{w3} \xi_{4i} \Delta GF_{t-i} + \sum_{c=0}^{w4} \xi_{5i} \Delta GDP_{t-i} +$$
$$+ \lambda ECT - 1 + vt_t \quad (5)$$

4. Results and Discussion

The findings displayed in Appendix "A" represent the descriptive statistics. In terms of the mean, EF shows the highest mean value (1.42E+08), followed by CH4 (160.7892), GTI (152.8882), CO_2 (145.5170), GF (48.43176), N_2O (40.47648), FD (19.02234), DEF (5.509949) and GDP (1.633036). In terms of dispersion, EF also shows the highest standard deviation (34,394,797), while DEF shows the lowest (0.555460), indicating that DEF is the most stable series over the sample period. The skewness values of CO_2, CH_4, DEF, N_2O, FD and GF are positive but close to zero, whereas EF and GDP are slightly negatively skewed, suggesting approximately symmetric distributions; however, GTI is considerably positively skewed (1.313398) with a kurtosis value above 3 (3.669563), indicating a leptokurtic distribution. Meanwhile, the Jarque-Bera probabilities of CO_2, EF, CH_4, DEF, N_2O, FD, GDP and GF are greater than 0.05, which shows that these variables are normally distributed, whereas the Jarque-Bera probability of GTI (0.005489) is less than 0.05, which shows that GTI is not normally distributed.

Prior to estimation, all variables are subjected to Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests to guard against spurious regression arising from non-stationary processes. The results of table 2 confirm that CO_2, ecological footprint, CH_4, N_2O, GTI, financial development, and green finance achieve stationarity at first difference I(1), while GDP and DEF exhibits stationarity at both level and first difference I(0)/I(1), confirming the mixed integration order that renders the ARDL bounds testing approach most appropriate for this analysis.

Table 2: Unit Root Test

Variable	ADF		PP	
	Level	1st diff	Level	1st diff
CO_2	-1.368	-2.814*	-1.374	-2.814*
EF	-2.498	-3.382**	-2.498	-3.345**
DEF	-2.719*	-5.829***	-3.126**	-5.955***
N_2O	-2.109	-2.178**	-1.021	-2.155**
CH_4	-1.297	-2.157**	-1.355*	-1.605**
GTI	-0.142	-4.337***	0.337	-4.405***
FD	-0.990	-5.181***	-0.631	-5.181***
GF	-2.397	-2.744***	0.020	-2.745***
GDP	-3.329**	-3.777**	-2.902*	-3.592**

Cointegration is confirmed when the computed F-statistic exceeds the upper critical bound I(1), while values below the lower bound I(0) indicate no long-run relationship, and those falling within the bounds yield an inconclusive determination. The bounds test results in table 3 confirm the presence of long-run cointegration across all estimated models.

Table 3 : F-Bound Test (ARDL)

ARDL Estimation						NARDL Estimation					
	CO_2	EF	CH_4	N_2O	DEF		CO_2	EF	CH_4	N_2O	DEF
F-Stat	5.14	8.32	7.10	8.25	7.09	F-Stat	5.16	6.72	9.09	5.87	9.23
C.V	I(0)	I(1)				C.V	I(0)	I(1)			
10%	2.45	3.52				10%	2.26	3.35			
5%	2.86	4.01				5%	2.62	3.79			
1%	3.74	5.06				1%	3.41	4.68			

The long-run ARDL results (Table 4) show an inverse relationship between GTI and environmental degradation across nearly all environmental proxies. The negative GTI coefficient suggests it plays a mitigating role in environmental sustainability. A unit rise in GTI reduces CO2 emissions, EF, CH4, N_2O and deforestation by 0.52%, 0.02%, 0.29%, 0.34% and 0.43% respectively in Pakistan. Green technologies, such as renewable energy sources, energy-efficient systems, and carbon capture, are designed to cut these emissions, reduce dependence on fossil fuels, and improve resource efficiency, thereby lowering ecological footprint and helping address climate change.

The GF coefficient is significant and negative, implying that an upswing in green finance reduces environmental degradation in both the short and long run. Green finance directs funds to renewable energy systems, sustainable agricultural methods, and energy-efficient infrastructure, directly reducing carbon, methane, and nitrous oxide emissions and the overall ecological footprint. This underscores its role in the shift toward a low-carbon economy and sustainable development.

In the short and long run, the rise of FD will result in the decrease of environmental degradation indicators, and the elasticity of FD is significantly negative. An advantage of FD is that it helps reduce CO2 emissions, contributing to environmental sustainability. GDP growth is positively related with environmental degradation. This is the traditional way of growth, depending on industrialization and resource utilization: the more the GDP grows, the more energy is required, the more fossil fuels are used up, and the more agriculture is intensified, leading to higher carbon, methane and nitrous oxide emissions and ecological footprints. This emphasizes the economic growth versus ecological sustainability dichotomy and the need to move towards sustainable economic practices and decoupling GDP growth from environmental damage.

Examining the asymmetric impact of green technological innovation on environmental sustainability we have found that environmental sustainability is highly affected by GTI positive shocks, which means that increasing green technological innovation will decrease CO2 emission, EF, CH4, N2O and deforestation, however, negative shocks of green technological innovation will boost CO2 emission, EF, CH4, N2O and deforestation. The long run results of NARDL indicated that one unit expansion in GTI will be responsible

for -0.64% decline in CO2 emissions, -0.53% drop in EF, -0.76% decrease in CH4, -0.43% wane in N2O, and -0.27% reduction in DEF. The results revealed that in positive shocks of GTI played a complementing role in environmental sustainability by mitigating CO2 emissions, yet in negative shocks, GTI played a devastating role in environmental sustainability by amplifying CO2, EF, N2O, CH4 and DEF. Our findings match with Du et al. (2019) and Rafique et al. (2020). The NARDL shows that there is a negative relationship between the N2O, CH4, DEF, EF and CO2 emissions and GF. This type of association means that the environmental sustainability of GF is positive; CO2 emissions, EF, N2O, CH4 and DEF are mitigated. The results indicate that for each unit increase in GF, the CO2 emissions, EF, CH4, N2O and deforestation will decline by –0.07%, –0.06%, –0.09%, –0.33% and –0.08%, respectively but with varying levels of significance. Our findings are similar with Ren et al (2020) for China. The effect of GDP on the quality of the environment was determined positive after evaluating the relationship between GDP and environmental quality. The correlation between GDP and environmental sustainability is positive and shows the disastrous effect of GDP on environmental sustainability. The relationship is nature which implies that GDP is harmful to the environment by contributing to its pollution. Our result is similar to that of Khan et al. (2020) in the case of China. FD has different association to various indicators of environmental sustainability. We obtain the same results as Ahmad et al. (2020) in the BRI countries.

Table 4: ARDL& NARDL Long Run Estimates

	ARDL Long Run Estimates				
	CO_2	**EF**	**CH_4**	**N_2O**	**DEF**
GTI	-0.52***	-0.02**	-0.29***	-0.34**	-0.43**
GTI Pos	-	-	-	-	-
GTI- Neg	-	-	-	-	-
GF	-0.03*** [0.11]	-0.08*** [0.04]	-0.15** [0.21]	-0.06** [0.07]	-0.04** [0.02]
GDP	1.24*** [0.04]	0.33*** [0.18]	0.28 [0.04]	0.31*** [0.03]	0.13** [0.04]
FD	-0.04*** [0.11]	-1.03* [0.12]	-0.14** [0.05]	-0.05** [0.13]	-0.48*** [0.12]
C	3.52*** [0.69]	6.60*** [1.14]	10.50** [0.87]	9.05*** [0.47]	9.45*** [0.20]
	ARDL Long Run Estimates				
	CO_2	**EF**	**CH_4**	**N_2O**	**DEF**
GTI	-	-	-	-	-
GTI Pos	-0.64*** [0.23]	-0.53** [0.092]	-0.76** [0.13]	-0.43*** [0.08]	-0.27*** [0.13]
GTI- Neg	-0.78*** [0.27]	-0.64*** [0.05]	-0.98*** [0.54]	-0.23*** [0.34]	-0.32*** [0.37]
GF	-0.07*** [0.15]	-0.06*** [0.07]	-0.09** [0.11]	-0.33** [0.05]	-0.08** [0.11]
GDP	0.24*** [0.15]	0.37*** [0.24]	0.14** [0.08]	0.06** [0.03]	0.34*** [0.02]
FD	-0.06*** [0.03]	-0.24*** [0.13]	-0.07** [0.09]	-0.04** [0.15]	-0.02*** [0.05]
C	-10.63*** [1.45]	7.25*** [0.54]	2.13*** [0.28]	3.19*** [0.52]	-1.45*** [0.26]

Note: *,**,*** represents 10%, 5%, & 1% significance level

Table 4: (Continued): ARDL & NARDL Short Run Estimates

ARDL					
	CO2	**EF**	**CH4**	**N_2O**	**DEF**
D(CO_2)	-0.45** [0.18]	-	-	-	
D(EF)	-	-0.52** [-1.09]	-	-	-
D(CH4)			0.41*** [0.32]		-
D(CH4 (-1))			0.53** [0.21]		-
D(N_2O)				0.21** [0.22]	-
D(N_2O(-1)					
D(DEF)					0.08** [0.13]
D(GTI)	-0.02*** [0.01]	-0.31** [0.09]	-0.12 [0.03]	-0.54*** [0.09]	-0.10** [0.06]
D(GTI)(-1))	-	-0.15*** [0.08]	0.01 [0.01]	-	0.09** [0.05]
D(GTI)(-1))	-	-	-0.05 [0.23]	-	-
D(GTI-Pos)	-	-	-	-	-
D(GTI-Pos(-1))	-	-	-	-	-
D(GTI-Pos(-2))	-	-	-	-	-
D(GTI-Neg)	-	-	-	-	-
(GTI-Neg(-1)	-	-	-	-	-
D(GF)	-1.14** [0.14]	-0.27** [0.18]	-0.218 [0.15]	-0.29** [0.10]	-0.09** [0.03]
D(GF(-1))	0.53* [0.26]	-	0.29** [0.34]	-	0.23** [0.02]
D(GDP)	0.74*** [0.07]	0.003*** [0.16]	0.03* [0.06]	0.02*** [0.04]	0.10** [0.02]
D(GDP(-1))	-	0.23** [0.04]	-	-	-
D(FD)	-0.009*** [0.07]	-0.04** [0.05]	-0.07 [0.15]	-0.01 [0.02]	-0.03** [0.09]
D(FD)(-1))	-	0.58** [0.12]	0.93** [0.23]	-	0.02** [0.19]
D(FD)(-2))	-	-	0.65** [0.13]	-	-
CointEq(-1)	-0.10*** [0.09]	-0.65** [0.20]	-0.37*** [0.05]	-0.53*** [0.06]	-1.09** [0.04]

Note: *,**,*** represents 10%, 5%, & 1% significance level

Table 4: (Continued): ARDL & NARDL Short Run Estimates

NRDL					
	CO2	**EF**	**CH4**	**N_2O**	**DEF**
D(CO_2)	-	-	-	-	-
D(EF)	-	-	-	-	-
D(CH4)	-	-	-	-	-
D(CH4 (-1))	-	-	-	-	-
D(N_2O)	-	-	-	-0.15** [0.09]	-
D(N_2O(-1)	-	-	-	0.13** [0.08]	-
D(DEF)		-	-	-	-
D(GTI)	-	-	-	-	-
D(GTI)(-1))	-	-	-	-	-
D(GTI)(-1))	-	-	-	-	-
D(GTI-Pos)	-0.40* [0.14]	-0.31** [0.11]	-0.46** [0.05]	-0.33** [0.09]	-0.31** [0.11]
D(GTI-Pos(-1))	-0.10** [0.21]	0.25*** [0.09]	-	-	-0.35** [0.12]
D(GTI-Pos(-2))	-0.30*** [0.133]	-	-	-	-
D(GTI-Neg)	-0.02** [0.04]	-0.27* [0.07]	-0.05** [0.05]	-0.04** [0.01]	-0.03** [0.01]
(GTI-Neg(-1)	0.03** [0.02]	-	-	-	-
D(GF)	-0.03 [0.32]	-0.10** [0.06]	-0.01** [0.12]	0.004* [0.03]	-0.15 [0.09]
D(GF(-1))	-	-0.02** [0.01]	-	-	0.27 [0.21]
D(GDP)	0.51** [0.30]	0.07** [0.01]	0.09** [0.03]	0.08 [0.06]	0.16 [0.12]
D(GDP(-1))	-1.09** [0.43]	-	-	-	-
D(FD)	-0.07** [0.01]	-0.74** [0.15]	-0.10** [0.06]	-0.80** [0.16]	-0.04* [0.03]
D(FD)(-1))	-0.05** [0.01]	0.21** [0.16]	-	-	-0.44* [0.17]
D(FD)(-2))	-	-	-	-	-
CointEq(-1)	-1.32*** [0.24]	-1.14** [0.19]	-1.62** [0.03]	-0.51*** [0.12]	-1.16*** 0.19

Note: *,**,*** represents 10%, 5%, & 1% significance level

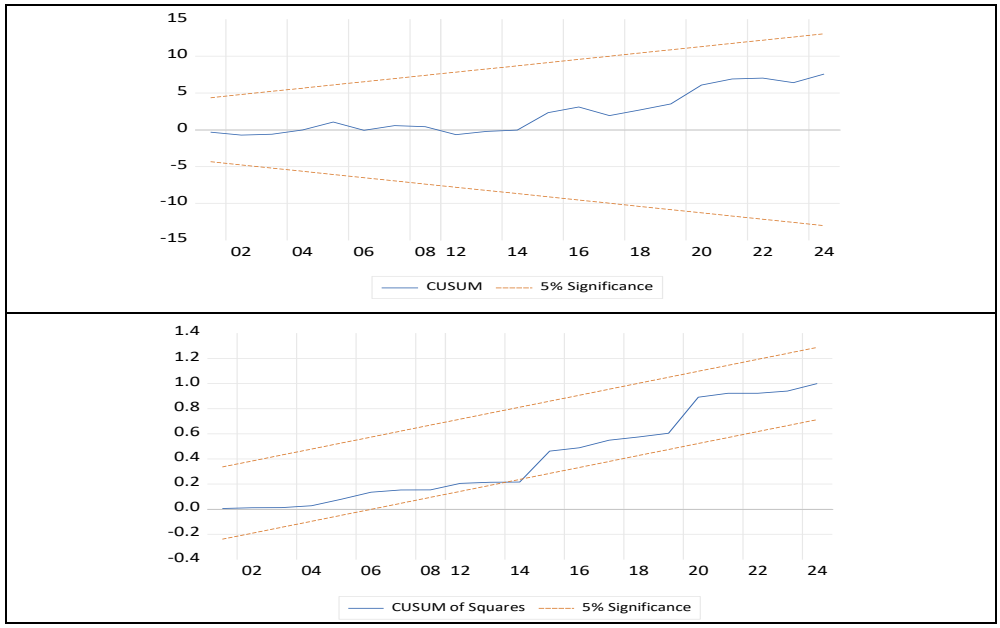
The error correction terms are negative and statistically significant in all models, confirming a stable long-run relationship. Several coefficients lie between −1 and −2. This does not indicate instability. It implies that deviations from long-run equilibrium are corrected within one year, with the adjustment overshooting the equilibrium and converging through dampened oscillations rather than monotonically (Narayan & Smyth, 2006). Since all coefficients are greater than −2, the adjustment process remains convergent (Loayza & Rancière, 2006).

Diagnostic test results in table 5 confirm that all ARDL and NARDL models are free from heteroscedasticity, autocorrelation, and normality violations, with stable parameter estimates throughout. The following graphs of CUSUM and CUSUMQ shows the stability. Wald test results further validate significant asymmetric effects across most models, with CO_2 and deforestation exhibiting the strongest asymmetry, followed by ecological footprint and N_2O, while CH_4 models display comparatively modest and less consistent asymmetric patterns.

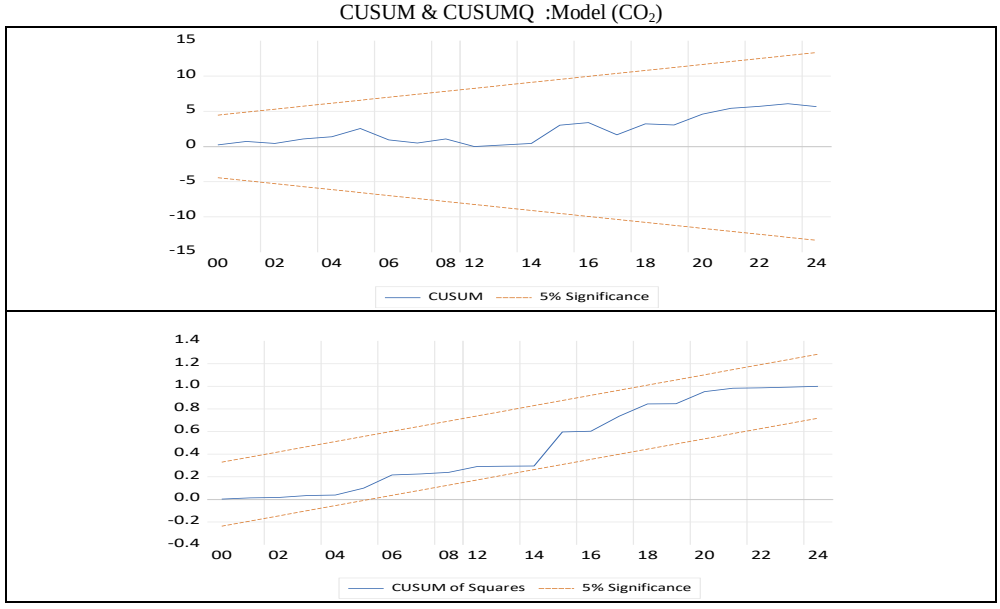
Table 5: Diagnostic Test (ARDL & NARDL)

ARDL					
	CO_2	EF	CH_4	N_2O	DEF
R^2	0.98	0.97	0.98	0.98	0.97
Adj R^2	0.97	0.96	0.97	0.97	0.96
D.W	2.18	2.16	2.09	2.19	2.34
LM test	0.27(0.65)	1.62(0.29)	0.15(0.68)	1.05(0.28)	0.25(0.49)
Hetero	1.29(0.11)	0.63(0.64)	0.59(0.50)	1.09(0.29)	0.43(0.32)
J.B	1.13(0.47)	0.45(0.65)	0.78(0.59)	0.25(0.23)	1.12(0.47)
Ramsey reset	0.29(0.53)	0.05(0.68)	0.10(0.27)	1.09(0.33)	0.82(0.49)
W_{SR}	-	-	-	-	-
W_{LR}	-	-	-	-	-
CUSUM	S	S	S	S	S
CUSUMQ	S	S	S	S	S
NARDL					
	CO_2	EF	CH_4	N_2O	DEF
R^2	0.98	0.95	0.98	0.98	0.97
Adj R^2	0.96	0.94	0.97	0.97	0.96
D.W	2.21	2.03	2.11	2.18	2.33
LM test	1.24(0.34)	0.54(0.61)	0.64(0.25)	0.19(0.74)	0.23(0.34)
Hetero	0.39(0.80)	0.29(0.76)	0.87(0.30)	1.31(0.19)	0.29(0.28)
J.B	1.31(0.29)	0.23(0.19)	0.55(0.54)	0.12(0.65)	0.54(0.29)
Ramsey reset	0.32(0.24)	0.41(0.09)	1.34(0.37)	1.56(0.89)	0.81(0.21)
W_{SR}	10.76(0.001)	7.32(0.043)	5.12(0.032)	6.02(0.012)	11.08 (0.002)
W_{LR}	12.78(0.001)	9.89(0.004)	8.54(0.06)	5.17(0.067)	7.56 (0.031)
CUSUM	S	S	S	S	S
CUSUMQ	S	S	S	S	S

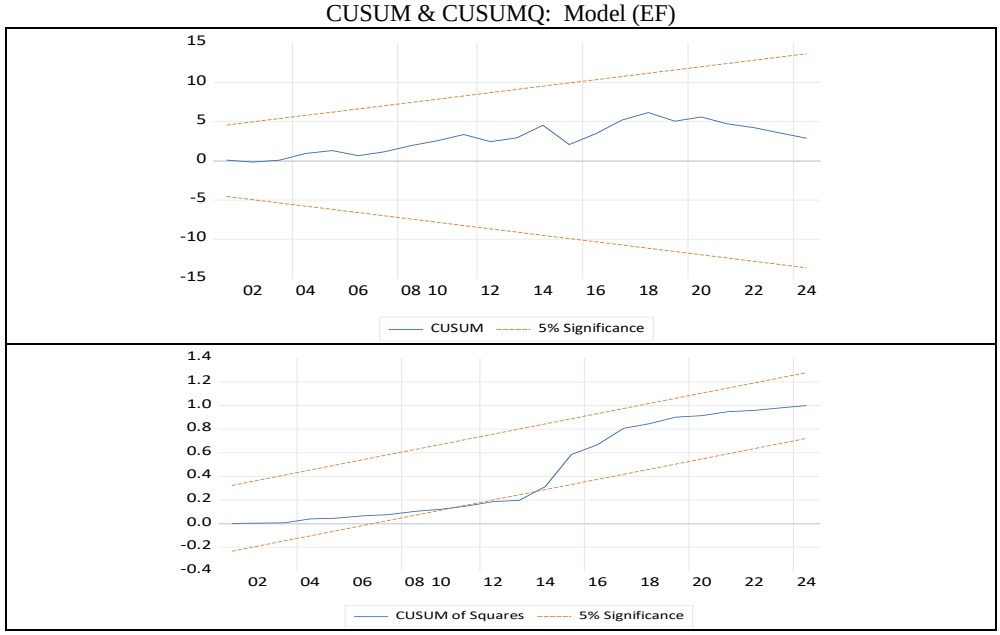
Graphs CUSUM & CUSUMQ (ARDL) Results



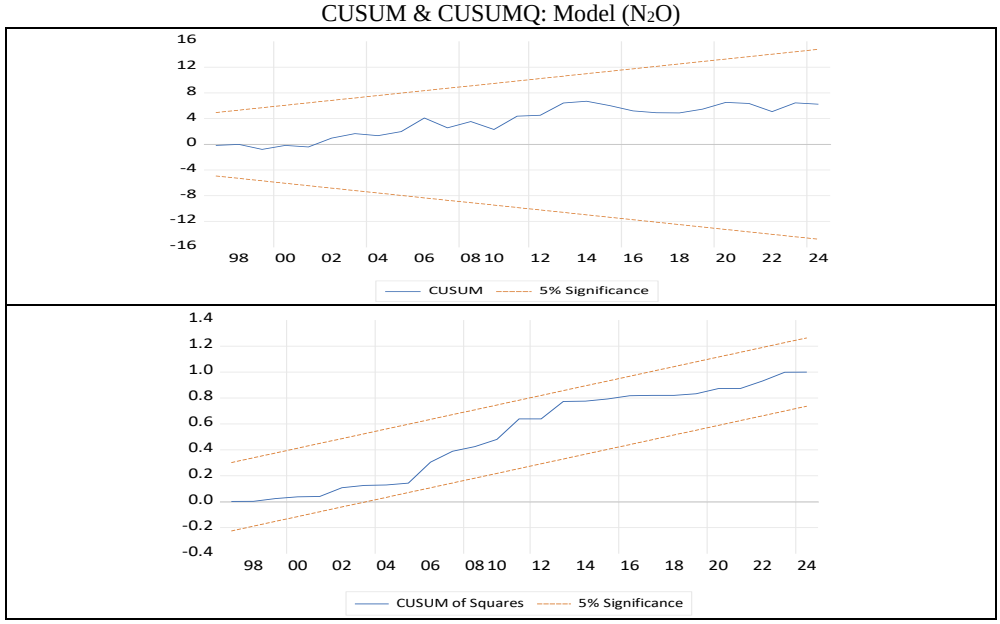
CUSUM & CUSUMQ :Model (CO_2)



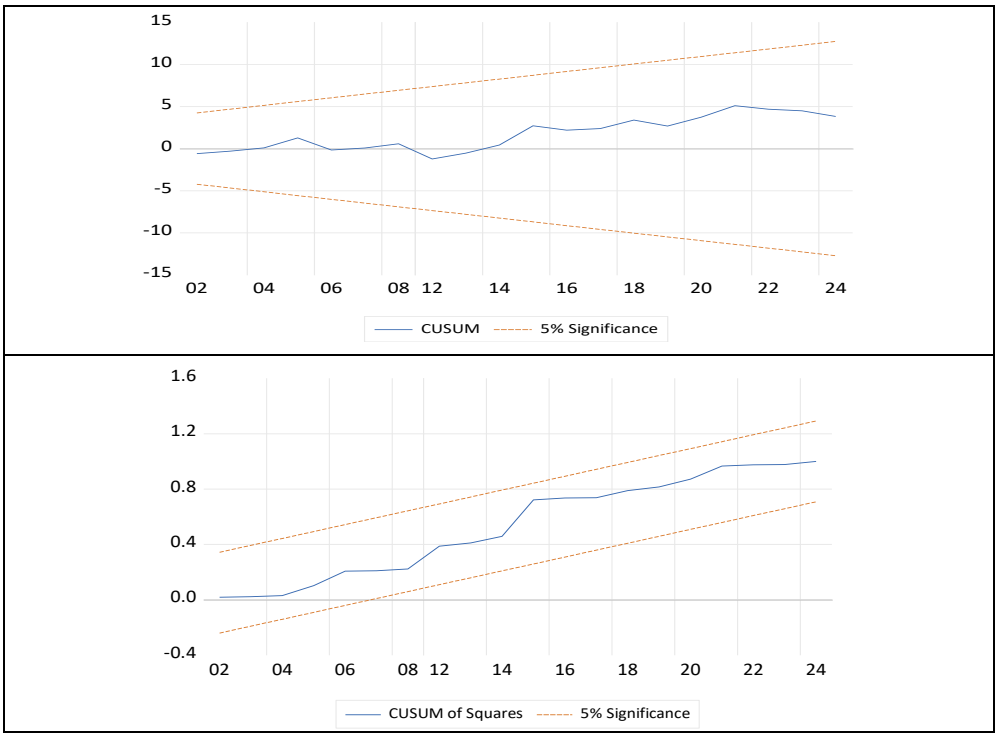
CUSUM & CUSUMQ: Model (EF)



CUSUM & CUSUMQ: Model (N_2O)

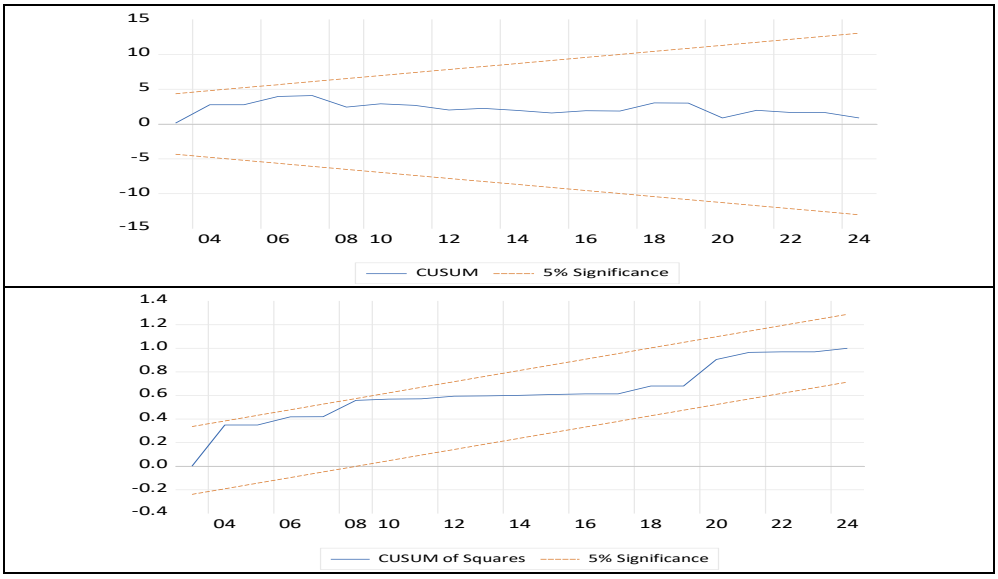


CUSUM & CUSUMQ: Model (CH_4)

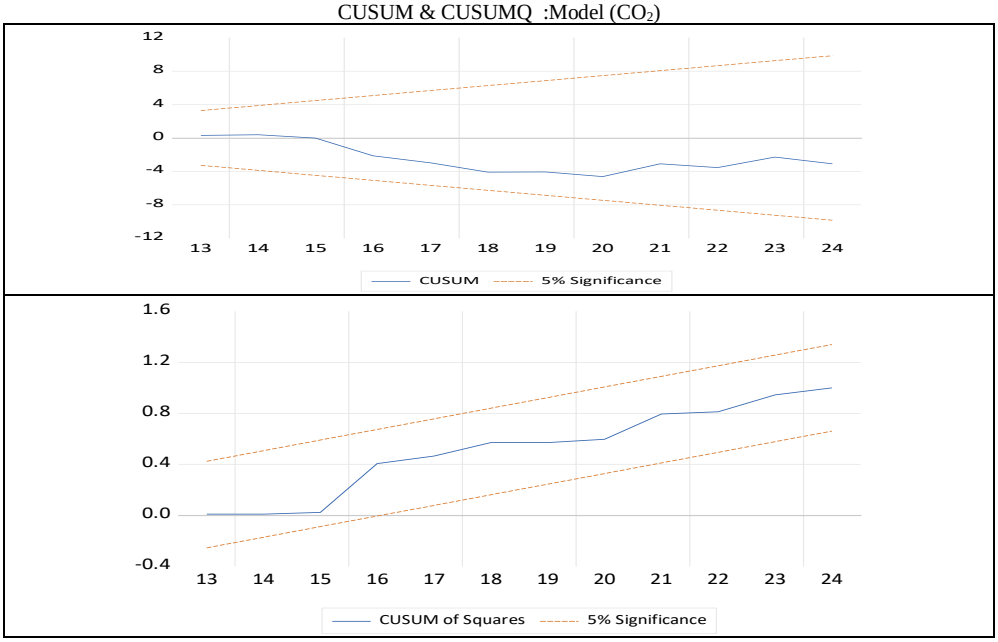


CUSUM & CUSUMQ: Model (DEF)

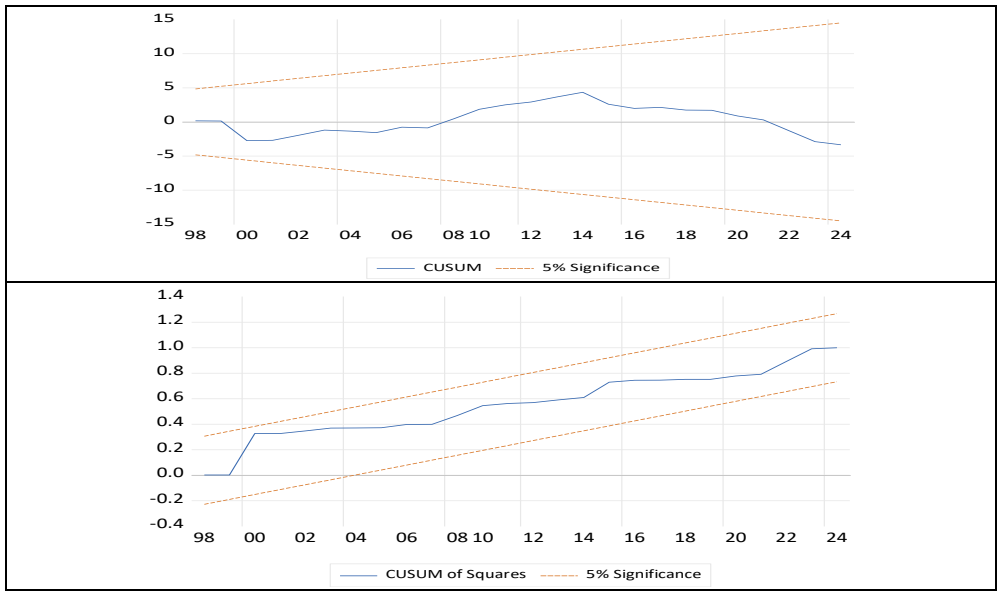
Graphs CUSUM & CUSUMQ (NARDL) Results



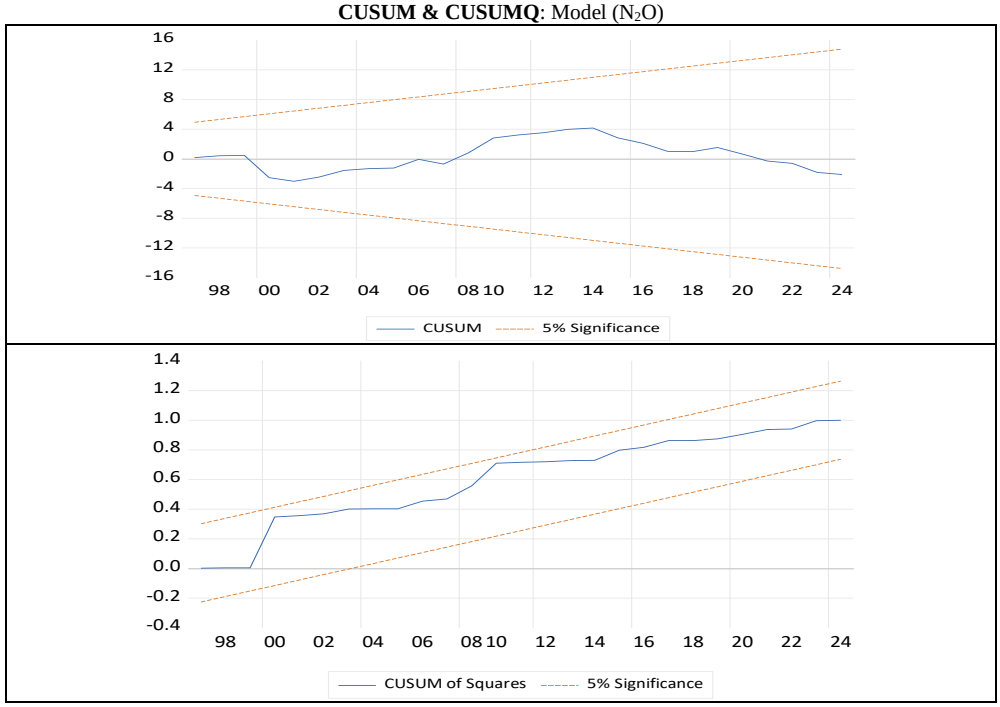
CUSUM & CUSUMQ :Model (CO_2)



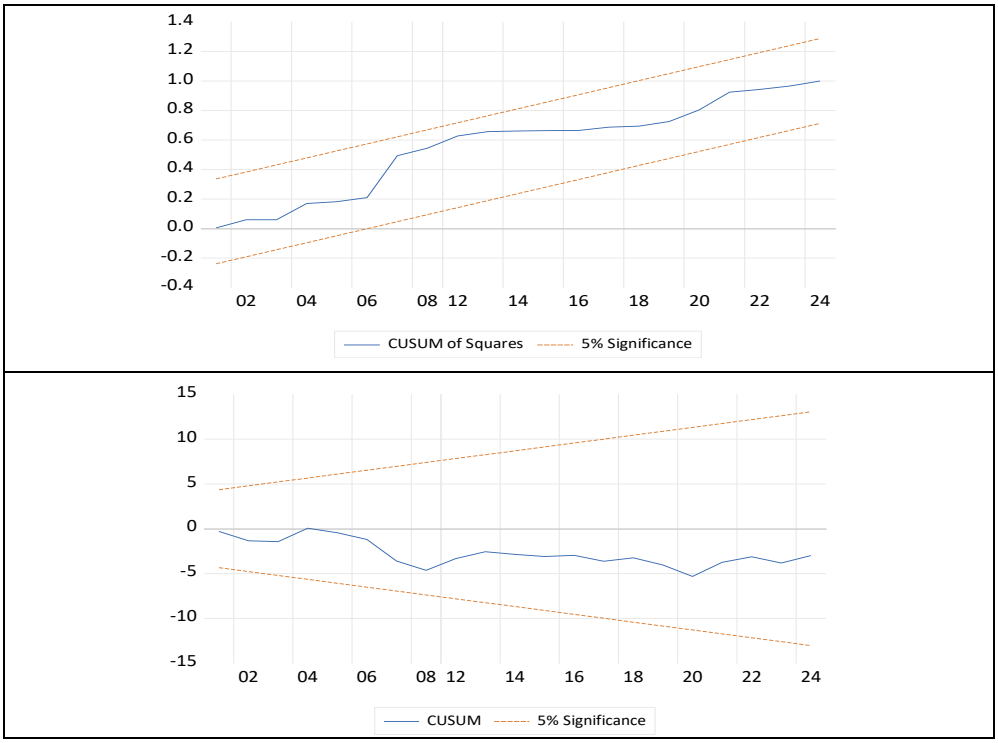
CUSUM & CUSUMQ: Model (EF)



CUSUM & CUSUMQ: Model (N_2O)



CUSUM & CUSUMQ: Model (CH_4)



CUSUM & CUSUMQ: Model (DEF)

5. Concluding Remarks and Policy Implications

This study examines the effects of green technological innovation (GTI), green finance (GF), financial development (FD) and GDP on environmental quality in Pakistan over 1990–2024 using ARDL and NARDL approaches. Five indicators are used: CO2 emissions, ecological footprint, methane, nitrous oxide and deforestation. The ARDL results show that GTI and GF are associated with lower environmental degradation, while GDP increases it, which is consistent with the rising part of the environmental Kuznets curve. The NARDL results confirm an asymmetric GTI–environment relationship: positive shocks to GTI reduce degradation, whereas negative shocks increase it. Green finance improves environmental quality across the indicators, while the effect of financial development varies by indicator. This suggests that its environmental impact depends on where credit is directed. Because these indicators reflect different sources of pressure, policy should be targeted. CO2 emissions and the ecological footprint call for renewable electricity, industrial energy efficiency, and green finance for power-sector and industrial decarbonization. Methane and nitrous oxide, which come mainly from agriculture, require

climate-smart practices such as improved livestock and manure management, biogas, efficient fertilizer use, and green credit for farmers. Deforestation requires stronger forest governance, afforestation, and wider access to clean cooking fuels to reduce fuelwood demand. Financial sector policy should also introduce environmental screening of lending so that credit expansion supports low-emission activities. Overall, green innovation and green finance can improve environmental quality in Pakistan, but only if they are aligned with the specific sources of each type of degradation.

But in Pakistan, the energy transition is hindered by circular debt, capacity payments to independent power producers (IPPs), and minimal grid capacity. Policy should thus operate within these parameters. First, new renewables will be tendered through competitive auctions without take-or-pay arrangements, and will replace high-cost imported-fuel generators, not be added to spare capacity. The savings to be realized as a result of renegotiating the IPP contracts should be used to pay down circular debt. Second, rooftop solar must be deployed via net-metering buyback rates reduction and time-of-use tariffs, rather than simply reducing buyback rates, without negatively impacting utilities' revenue. Third, increasing transmission and adding grid-scale storage must precede additional renewables goals. Fourth, a reasonable wheeling charge would enable the industry to purchase green power directly, and attract private investment in clean energy by implementing the Competitive Trading Bilateral Contract Market (CTBCM). Last but not least, distribution losses reduction and energy-efficiency standards can be applied at low cost to alleviate fiscal burden and emissions. These debt easing measures must be taken before the expansion of capital investment that is implemented with limited fiscal space in Pakistan.

There are some limitations to this study. First, the proxy of patents in the area of environment may underestimate the innovation in the case of Pakistan as a large amount of green technology is imported rather than invented domestically. Second, the green finance data is of limited time horizon and is based on proxies since the market of green bonds and green credit is still nascent in Pakistan.

These limitations could be overcome in future studies in the following ways. It may involve variables like (institutional quality, as measured by the World Governance Indicators), urbanization, energy intensity (energy efficiency measure) and energy consumption from renewable sources (explanatory variable). It could include a wider range of measures of environmental quality, such as the ecological footprint or load capacity factor, and could include technology imports (e.g., importation of solar panels) to better capture green innovation. A pandemic dummy can be used for structural breaks such as the COVID-19 pandemic, or can be analyzed by using Bai–Perron break tests and Fourier ARDL. Lastly, the relationship between these parameters might shift in periods of different emissions intensities and time scales, which could be identified using quantile ARDL (QARDL) or wavelet coherence.

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Declaration of AI Use

AI-assisted tools were used only for language refinement and grammar correction across the manuscript text, not for data collection, analysis, interpretation, or any scientific content, and the authors reviewed all edits and take full responsibility for the work.

Data Availability

The data will be made available from the corresponding author upon reasonable request.

Declaration of Conflict of Interest

The authors declare no financial competing interests relevant to this study.

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Appendix A

Table A: Descriptive Statistics

	CO2	EF	CH_4	DEF	N_2O
Mean	145.5170	1.42E+08	160.7892	5.509949	40.47648
Median	150.2752	1.45E+08	155.0055	5.500033	39.80905
Maximum	235.3725	2.04E+08	250.9017	6.468958	59.45200
Minimum	65.64050	87118520	97.98770	4.618799	23.39610
Std. Dev.	50.52651	34394797	47.30910	0.555460	11.18454
Skewness	0.152540	-0.021042	0.354385	0.095944	0.149539
Kurtosis	1.837069	1.839791	1.852951	1.810745	1.765405
Jarque-Bera	2.047767	1.909463	2.575607	2.055796	2.286036
Probability	0.359197	0.384916	0.275876	0.357758	0.318855
Sum	4947.576	4.83E+09	5466.834	187.3383	1376.200
Sum Sq. Dev.	84246.62	3.90E+16	73858.98	10.18170	4128.103
Observations	34	34	34	34	34
	GTI	**FD**	**GDP**	**GF**	
Mean	152.8882	19.02234	1.633036	48.43176	
Median	94.00000	17.50582	1.590943	47.65000	
Maximum	564.2000	25.47432	5.202456	58.10000	
Minimum	16.00000	11.46062	-3.038893	41.60000	
Std. Dev.	154.0668	4.488972	2.123956	4.604294	
Skewness	1.313398	0.056154	-0.122597	0.327274	
Kurtosis	3.669563	1.458876	2.424414	2.234883	
Jarque-Bera	10.41020	3.382540	0.554511	1.436268	
Probability	0.005489	0.184285	0.757861	0.487661	
Sum	5198.200	646.7597	55.52323	1646.680	
Sum Sq. Dev.	783307.5	664.9786	148.8693	699.5843	
Observations	34	34	34	34	