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Asymmetric Effect of Innovation on Environmental Quality Based on Environmental Kuznets Curve: A Novel Approach

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Abstract
Environmental technologies and trade openness have distinct effects on environmental quality, and they are strongly associated with income and economic growth. The study looks at how trade openness impacts environmental quality in OIC countries between 1980 and 2023 using a range of environmental variables. A new methodology nonlinear autoregressive distributed lags (NARDL) is applied to resolve the issue of homogeneity and heterogeneity. The research has employed various carbon dioxide (CO2) proxies as measures of environmental quality, and a novel variable aims to address environmental issues in emerging nations such as Pakistan within a contemporary framework. Our research, which involved creating an index and applying Principal Component Analysis (PCA), demonstrates that in developing nations when environmental pollution occurs, the EKC has an Inverted-U form (CO2). The results of the NARDL technique demonstrate a strong positive association between CO2 and trade openness, environmental technology innovation (ENT), and economic growth. Furthermore, this study investigated nonlinearities not found in earlier studies and demonstrated some misleading decisions. Our results validate the existence of an Inverted-U-shaped EKC when CO2 is used as an environmental indicator in poor countries such as Pakistan. Ultimately, the argument is made that if developing countries continue their policies of economic openness, energy sector reforms, and renewable energy use, they will be able to use the increased cash to address environmental concerns.
Keywords: Technology Innovation, Economic Growth, Trade openness, NARDL

1. Introduction
Environmental pollution is the highest challenge of the world and it is damaging human beings. Increased energy consumption and economic activity (transportation, industrial output, and deforestation) lead to a decrease, as people's standard of living rises during the second stage of development as a result of the technology effect, they want cleaner environs. Thus, cleaner technology or the services sector replaces the production of goods based on impure technology, which has an environmentally beneficial effect known as the composition effect (Song et al., 2024; Sadia Bint Raza et al., 2024; Ali & Audi, 2016). Innovations are thought to be the primary force behind economic expansion. As countries continue to expand economically. A developing economy cannot exist without having an impact on the environment. Environmental quality can be impacted by technological advancements in a number of ways. Technology advancements lower production costs and boost production efficiency while promoting the study and development of new products (Amin et al., 2024; Zubair et al., 2024; Parveen et al., 2024).
Cost-benefit analyses may not necessarily result in technological advancements that are ecologically benign. Examples of technologies that have contributed to environmental deterioration include metal smelting, heavy chemical processing, nuclear. The question that arises in this case is whether technology advancements improve or worsen environmental quality. The worldwide mean temperature rose by one degree Celsius as a result of industrial and human-caused global warming. Between 2029 and 2051(Rabbia Syed, Sehrish Arshad, 2024; Shen et al., 2024). The location under investigation is among the top emitters in the globe, the average annual carbon dioxide emissions per person are 6.50 metric tons, compared to 4.70 metric tons globally (Huang et al., 2024). The transportation sector in Pakistan is primarily responsible for high energy consumption and environmental contamination. In Pakistan, issues of environmental distortion, poor fuel quality, and the rapidly expanding transportation sector all work against sustainable development. Pakistan has the highest global susceptibility to climate change (Arshad et al., 2024; Saeed et al., 2024; Tanveer Ahmad Shahid, 2023; Ali et al., 2021; Audi & Ali, 2017; Ali et al., 2022; Audi et al., 2020; Audi & Ali, 2023).
Half of the pollution is produced by the energy and transportation industries combined, which are the primary sources of pollution. The swift expansion of transportation modes deficient in high-quality fuel leads, according to (Nazik Maqsood, 2024; Shahid, 2024) technological innovation raises CO2 emissions in developing countries such as Pakistan. Pakistan's technology industry has been steadily growing over the past few years (Maqsood1 et al., 2023) Furthermore, Pakistan has more than 250 cities connected by a fiber-optic cable network. 76.38 million people were using the Internet as of January 2020, a 17% increase over 2019. Furthermore, 37 billion people in Pakistan use social media. Pakistan is currently experiencing an industrialization and urbanization period, driven by a rapid increase in energy demand (Minhas et al., 2024; Abro et al., 2024; Shahid et al., 2023; Ali et al., 2021).
The overall influence of trade openness, technology, and energy usage is what this study seeks to ascertain on the environmental quality in developing nations like Pakistan, driven by the resulting disagreement in the literature. Even though numerous research has discovered this impact in various economic groups, there are currently relatively few operations in this crucial area and no thorough studies on the topic in the case of Pakistan.

2. Literature review
Since its introduction in the early 1990s, EKC has been a household name, having served as the subject the employing the EKC theory, the results. was unable to identify the trade-environment link; however, the research did note it under the effects of method, scale, and composition. The EKC is the result of the combined effect of these three factors one of the key indicators that affect environmental quality, according to a number of research on environmental deterioration, is trade openness (Shahid, 2024b; Irfan et al., 2023; Ullah et al., 2023). The incidence of deforestation in OECD countries has dropped, according to a study that examined 142 countries and the effects of trade openness investigated the viability of the pollution refuge hypothesis in MENA countries using the fixed and random effect approach (Javaid et al., 2023; Awan et al., 2023; Chaudhary et al., 2023). The Middle East and North

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Africa region's environmental quality has improved due to foreign direct investment inflows, as demonstrated by the results, which also supported the pollution haven idea Numerous academics have discovered a link between environmental quality and technology developments in earlier studies (See Table 1It was also discovered that lowering CO2 emissions during the production process was a successful strategy for halting global warming. Similar to this used data from Chinese and French provinces, respectively, to discover a negative relationship between technical advancements and pollution (Zahra et al., 2023; Shahzadi et al., 2023; Zhao et al., 2023; Audi & Ali, 2023; Ashiq et al., 2023).
EKC was validated for 14 Asian countries using CO2 emissions. An Inverse-U-shaped relationship between GDP and environmental degradation was discovered after the GMM approach was used. The second body of research, on the other hand, contends that technological improvements have a negative effect on environmental quality. In their 2020 study, found that although technological advancements had positive environmental benefits, they also had negative effects. In a similar vein, the BRICS nations witnessed an increase in CO2 emissions in spite of economic progress (Dawood et al., 2023; Shahzadi, Ali, et al., 2023; Naz et al., 2022).

3. Data and methodology

Studies conducted to date have sought to evaluate the nonlinear effects on environmental quality of (TO), energy consumption, GDP, and environmental technology innovations (ENT). The years 1980–2023, inclusive, were included in the study. This regression model uses the environmental indicators (CO2) as dependent variables. Our independent variables include GDP per capita, trade openness, environmental technology, and per capita energy usage.

Table 1: Descriptive statistic

Variables	Symbols	Proxies/ Measurement of variables	Data-Source
Environmental Pollution	EN	“CO_2 emissions from transport (% of total fuel combustion n)	World development indicator
		Exports plus imports divided by GDP	
Trade Openness	TO	“(Number of Patent application, residents)	Economic Survey of Pakistan
			Economic development indicator
Technology Innovation	ET		
Economic Growth	GDP	Real GDP growth (constant US$ 2020)	World development indicator
Energy Consumption	EC	energy consumption (Billions of kilowatts)	World development indicator

4. Methodology

4.1. The asymmetric approach

As we debate in previous segment 1, generally, we inspected the standard time series association between the variables as “trade openness, environmental technology and environmental pollution” is measured traditionally, co-integration such as vector error correction approach, and granger causality (Ghazia Khoula, 2022). All of these tactics are used because it is thought that there is a direct correlation between environmental degradation and technology. However, the asymmetry relationship between the variables was not examined in the earlier studies, which used the ARLD co-integration based on the connections between the variables across both short and long terms. Asymmetric co-integration is the method used in the current investigation (Tabassum et al., 2023).
Moreover, the variables such as "trade openness, energy consumption, environmental technology innovation, and industrialization" were broken down into positive and negative independent variables using the bound asymmetric co-integration test. Because of the asymmetric approach, we are able to determine the non-linear relationship among the variables. Consequently, we assess the proposed variables' long-term relationship and generate the primary long-run equation as outlined below

$$z_t = \alpha_0 + \alpha_1(y_t) + \mu_t \qquad (1)$$

However, after every one of our variables reaches a stationary state, we can apply the long-run and short-run (ARDL) technique the initial difference I(1) or the level I (0) or get the mixed results as at level or first difference but this approach will be invalid on 2^{nd} difference I(2), stationary level (Rahman et al., 2022). Furthermore, according to (Qureshi et al., 2022) purposed variables have positive and negative impacts on them and also, they argued the ARDL co-integration approach does not elaborate on the hidden relationship among the variables. For instance, another author established the asymmetric techniques or the hidden co-integration among the variables for only one component of the series……

$$z_t = \theta + \theta^{+} y_t^{+} + \theta^{-} y_t^{-} + \mu_t \qquad (2)$$

The current study, as reported by (Li et al., 2022), employed the NARDL model to construct the NARDL dynamic cumulative multiplier equation.

$$n_l^{+} = \sum_{i}^{k} \frac{\partial y_{t-i}}{\partial y_t^{+}}$$

$$n_l^{-} = \sum_{i=0}^{k} \frac{\partial y_{t-i}}{\partial y_t^{-}} \qquad L = 0, 1, 2, 3, 4 \dots \dots .$$

Note: such that when L→∞, n_l^+→β^+ and n_l^-→β^-, where β^+ and β^- are the asymmetric long-run coefficients, are computed as follows.

5. Empirical results and findings

5.1. Descriptive statistic results

The present research scrutinizes the descriptive statistic, and unit root test and then evaluates the asymmetric This section contains both short- and long-term findings.

Table 2: Descriptive statistic

	LENP	LTRO	LENT	LGDP	LENC
Mean	4.533	4.677	3.219	-0.106	2.191
Median	4.531	4.659	3.231	-0.100	2.231
Maximum	4.544	4.800	3.298	0.428	2.294
Minimum	4.525	4.578	3.105	-0.725	1.915
Std. Dev.	0.006	0.060	0.053	0.384	0.099
Skewness	0.612	0.293	-0.546	-0.186	-1.112
Kurtosis	1.674	1.822	2.507	1.944	3.281
Jarque-Bera	19.830	10.529	8.745	3.755	30.61
Probability	0.000	0.455	0.212	0.152	0.337

The "Jarque-Bera" test establishes the normality of the data and shows that every variable—aside from the LENP variable, which performs exceptionally well—is bigger than the 1% level of significance.

5.2. Finding of unit root test

The present study uses two popular tests, Philip Peron (1988) and Augmented Dickey-Fuller (1979, At the significance levels of 1% and 5%, the means variables ** and *** demonstrate stationarity, respectively. Additionally, the information assesses the inconsistent outcomes, indicating that the current study moves on with the variables' unbalanced long- and short-run cointegration.

Table 3: unit root test

Variables	Unit root at level I(0)		Unit root at first difference I(1)	
	ADF	PP	ADF	PP
LENP	(0.434)	(0.379)	(0.000)***	(0.000)***
LTRO	(0.268)	(0.442)	(0.000)***	(0.000)***
LENT	(0.490)	(0.478)	(0.000)***	(0.000)***
LGDP	(0.818)	(0.478)	(0.000)***	(0.000)***
LENC	(0.059)**	(0.037)**	(0.000)***	(0.000)***

Note: Utilizing intercept and intercept and trend, the unit root tests for the augmented Dickey-Fuller (ADF) and Philip Peron (PP) were conducted at the level and first difference, respectively. The lag time is significant at 1% and 5%, respectively was chosen using the SBIC, which is displayed in the parenthesis * and **.

5.3. Bound test of linear and nonlinear cointegration

The symmetric and asymmetric bound testing cointegration technique findings are shown in Table 4. Results display both linear and nonlinear cointegration F-statistic observations. The results of the linear (ARDL) F-statistic value analysis point to an inconclusive outcome since the F-statistic computed value (0.826) is less than the lower bound value of 2.62 at a significance level of 1%. Thereby, the F-Statistic computation's nonlinear value (5.115) surpasses the top limit observation and this information provides a nonlinear relationship among the variables which means there is hidden cointegration exists between the environmental pollution (CO_2) and the exogenous variables of TRO, ENT, GDP, and ENC. In this model, the long- and short-term relationships between the endogenous and exogenous variables are being pursued because of the available data on cointegration among the variables (Zulfiqar et al., 2022).

Table 4: Bound test for linear and non-linear cointegration

			Critical values bounds		
Test-Statistic	F-Statistic	Sig. level	Lower bound at 5%	Upper bound at 5%	Decision
Linear ARDL	0.726	1%	2.62	3.77	Inconclusive
Asymmetric ARDL	5.115	5%	2.11	3.15	Cointegration exists
		10%	1.85	2.85	

Note: The high cointegration relationship is confirmed by the F-Statics value, which is greater than the upper limit value. The linear-ARDL critical value from Pesaran et al. (2001) represents the 1%, 5%, and 10% significance levels of the critical bound values, asymptotic cointegration's null hypothesis is $p = \theta^{+} = \theta^{-} = 0$

5.4. Dynamic asymmetric estimations

First, some diagnostic tests including serial correlation and heteroscedasticity are used in this study. At the 5% level of significance, table 5 shows that the data is not heteroscedastic or serially correlated. On the other hand, the R2 value shows that independent variables account for 87% of the change in dependent variables.

Table 5: Dynamic Asymmetric estimations

Variable	Coefficient	Prob.*
LNENP(-1)	-0.916	0.000***
LNTRO_POS	0.006	0.111***
LNTRO_NEG	0.005	0.228
LNENT_POS	0.234	0.000***
LNENT_POS(-1)	-0.219	0.000***
LNENT_NEG	-0.148	0.000***
LNENT_NEG(-1)	0.138	0.000***
LNGDP_POS	0.020	0.000***
LNGDP_POS(-1)	0.013	0.000***
LNGDP_NEG	0.009	0.004***
LNGDP_NEG(-1)	-0.009	0.004***
LNENC_POS	-0.081	0.000***
LNENC_POS(-1)	0.071	0.000***
LNENC_NEG	-1.523	0.000***
LNENC_NEG(-1)	1.443	0.001**
C	0.380	0.021**
R^2	0.867	
F-Statistic	217.657	
Serial correlation		0.331
Heteroscedasticity		0.371

5.5. Asymmetric short-run estimations

In Table 6.1, the current study aims to elucidate the outcome of the dynamic estimation for a brief time. According to the short-term equation, there is a 1% significance level for the dependent variable LNENP (-1) with a coefficient of -0.080. In the current model, the negative sign denotes a long-term association between the variables. Consequently, "trade openness (TRO)" shocks—both positive and negative—are significant in the short run. This suggests that there will be an increase equal to each unit growth in trade openness in environmental pollution of 0.053 units. This is because trade openness creates chances for green projects and loans, both of which reduce carbon emissions.

Table 6: Asymmetric short-run results

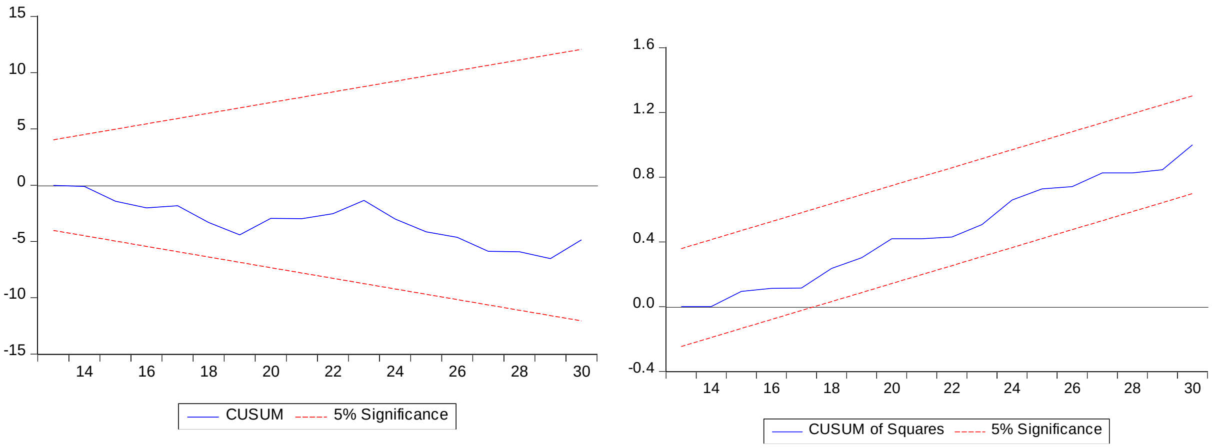
Variable	Coefficient	t-Statistic	Prob.
C	0.380	2.235	0.027**
LENP(-1)*	-0.080	-2.23	0.027**
LTRO_POS**	0.053	2.595	0.011**
LNTRO_NEG**	0.009	4.230	0.022**
LNENT_POS(-1)	0.016	1.19	0.025**
LNENT_NEG(-1)	-0.094	-3.978	0.036**
LNGDP_POS(-1)	-0.017	-2.876	0.033**
LGDP_NEG(-1)	-0.425	-5.043	0.097*
LNENC_POS(-1)	-0.094	-1.589	0.115
LNENC_NEG(-1)	-0.083	-0.490	0.620
d(LNTRO_POS)	0.232	9.750	0.000***
d(LNTRO_NEG)	-0.148	-6.283	0.000***
d(LNENT_POS)	0.028	-8.725	0.000***
d(LNENT_NEG)	0.002	3.615	0.004**
d(LNGDP_POS)	0.089	-6.553	0.000***
d(LNGDP_NEG)	-1.528	-4.249	0.000***
d(LNENC_POS)	0.179	-4.553	0.000***
d(LNENC_NEG)	-1.207	-3.942	0.000***

5.6. The asymmetric results of long-run

The variables' nonlinear long-run connection was presented in Table 7. According to the coefficients of LTRO_POS and LNTRO_NEG, which are significant at the 5% level of significance and 0.070 and 0.078, respectively, there is an unbalanced link between the variables. In poor nations like Pakistan, environmental pollution will also rise by 0.070 units for every 1% increase in "trade openness." Trade openness substantially lowers environmental pollution and advances the development of a sustainable ecosystem, according to (A. U. Shahid et al., 2022) thus, it is imperative that the Pakistani government offer investors opportunities to engage in carbon-neutral initiatives. Moreover, a strong correlation has been shown between trade openness and its negative shock. It follows that a 1% reduction in "trade openness" will translate into a 0.078-unit drop in CO2 emissions (ENP), indicating instability in the financial market and a lack of capital for investors or businesses to engage in pollution-reducing initiatives.

The efficiency of “technology innovation” enables the removal of polluted environment. Furthermore, the negative shock of environmental technology will reduce in CO_2 omission (ENP) reported the result of negative shock and it is significant which means 1 unit decreases in environmental technology will lead to reducing the ENP process and has the inverse relationship. Furthermore, the LNENC_POS and LNENC_NEG have the coefficients 0.192 these variables are significant at a 5% threshold of significance, meaning that and -0.393, respectively it is confirmed that there is asymmetric relationship is existing. However, the LNENC_NEG shock indicates the reduction of the CO_2 omission (ENP) and also has the inverse association between the variable. This means 1% decrease in energy consumption will lead to reduce the 0.393% of ENP because the environmental pollution process requires lots of demand energy consumption.

Model stability test



To examine the data stability in the model, Brown et al. (1975) suggested using CUSUM and CUSUMSQ. This is equally valid for the long-term stability of the coefficients. The results are steady, as shown by the blue lines in the previously mentioned figures, which lie between the upper and lower critical bounds at a 5% level of significance. This proves the stability of the coefficients.

6. Conclusion and policy implication

To address the issue of homogeneity, the study has adopted a novel methodology called nonlinear autoregressive distributed lags (NARDL). EKC is found in poor nations such as Pakistan, according to NARDL estimate. The eventual improvement in Pakistan's environmental quality is encouraged by the validation of EKC in our model. Additionally, the findings demonstrate that trade openness ought to be preserved since it enhances environmental quality and promotes sustained EG, particularly in developing nations where it is beneficial for gaining comparative advantages and the composite effect. The findings imply that Pakistan ought to employ suitable policy instruments to reroute technology advancements brought about by trade and capital inflows in the direction of the (SDGs). Furthermore, trade liberalization is contributing to an increase in pollution in Pakistan. Therefore, in order to regulate industrial activity, these nations should enact stringent environmental rules. The industries that produce the most pollution Should be liable to penalties and assessments for contamination. These pollution fees can be used to fund government initiatives aimed at maintaining environmental quality. One major factor contributing to environmental quality is the energy industry's compositional influence.

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