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Examining the Nonlinear Dynamics of Trade Openness and Environmental Quality in Organization of Islamic Cooperation Countries

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Abstract
This research examines the influence of trade openness on environmental quality in Organization of Islamic Cooperation countries from 1990 to 2023, focusing on various environmental variables. The study employs a novel approach using the nonlinear autoregressive distributed lags model to address issues of homogeneity and heterogeneity in data analysis. It utilizes different carbon dioxide proxies to assess environmental quality, introducing an innovative variable tailored to emerging nations. By creating an index and employing Principal Component Analysis, our findings highlight that environmental pollution in developing countries typically exhibits an Inverted-U curve relationship with carbon dioxide levels. The nonlinear autoregressive distributed lags analysis reveals a strong positive correlation between carbon dioxide emissions, trade openness, environmental technology innovation, and economic growth. Additionally, this study explores nonlinearities previously undetected, uncovering some decisions that might have been misguided. The results confirm the presence of an Inverted-U-shaped Environmental Kuznets Curve when using carbon dioxide as an environmental indicator in less affluent nations. The study concludes with a robust argument advocating for continued policies of economic openness, energy sector reforms, and increased use of renewable energy in developing countries. Such strategies are essential for these nations to utilize additional financial resources effectively to tackle environmental challenges.
Keywords: *Trade Openness, Environmental Quality, Nonlinear Autoregressive Distributed Lags*
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1. INTRODUCTION

Environmental pollution remains one of the most pressing global challenges, posing significant threats to human well-being (Singh & Singh, 2016). The increasing consumption of energy and the expansion of economic activities, including transportation, industrial production, and deforestation, contribute to environmental degradation. However, as economies progress through different stages of development, a shift in environmental priorities often occurs. During the second stage of development, rising living standards and technological advancements encourage a growing demand for cleaner surroundings. This shift leads to the replacement of outdated, pollution-intensive production methods with cleaner technologies or a transition towards a service-oriented economy (Tao et al., 2024). This transformation, often referred to as the composition effect, results in positive environmental outcomes by reducing reliance on environmentally harmful industrial processes (Akim, 2020; Altaf & Shahzad, 2021; Song et al., 2024; Sadia et al., 2024; Marc et al., 2024). Innovation is widely regarded as a key driver of economic growth, enabling nations to expand their economies while addressing environmental concerns. As countries continue to experience economic progress, it becomes evident that development cannot occur without impacting the environment in some way (Qamruzzaman & Karim, 2024; Roussel & Audi, 2024). However, technological advancements play a crucial role in shaping the relationship between economic growth and environmental sustainability. Innovations in technology contribute to lower production costs and enhanced efficiency, while also encouraging research and the development of sustainable solutions. Advancements in cleaner technologies not only support industrial expansion but also help mitigate environmental damage by promoting energy efficiency and reducing emissions (Marc & Ali, 2023; Aydemir, 2024; Amin et al., 2024; Zubair et al., 2024; Parveen et al., 2024). By integrating innovative technologies into economic

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frameworks, nations can achieve a balance between development and environmental conservation. The role of technology in fostering sustainable growth underscores the need for policies that support research, innovation, and the adoption of cleaner industrial processes. As global economies advance, fostering a transition toward environmentally sustainable technologies and energy-efficient production systems will be critical in mitigating the negative consequences of economic expansion.
Cost-benefit analyses do not always lead to technological advancements that are environmentally sustainable. Several industrial technologies have significantly contributed to environmental degradation, including metal smelting, heavy chemical processing, and nuclear energy production. These technologies, while enhancing economic productivity and industrial growth, have also resulted in severe ecological consequences, raising the critical question of whether technological progress improves or worsens environmental quality. One of the most alarming consequences of industrialization and human-induced global warming is the increase in the global mean temperature, which has risen by approximately one degree Celsius. Projections indicate that between 2029 and 2051, climate change will continue to intensify, leading to further environmental instability (James, 2020; Hussain & Khan, 2020; Marc, 2022; Rossi, 2023; Rabbia et al., 2024; Shen et al., 2024). The region under analysis is among the highest carbon dioxide emitters in the world. The average annual carbon dioxide emissions per capita stand at 6.50 metric tons, surpassing the global average of 4.70 metric tons (Huang et al., 2024). Such high levels of emissions highlight the urgent need for adopting sustainable energy practices and transitioning toward greener technologies. Among the various sectors contributing to environmental degradation, the transportation sector plays a dominant role in escalating energy consumption and pollution levels. The country faces critical environmental challenges, including increasing carbon emissions, poor fuel quality, and the rapid expansion of the transportation sector, all of which hinder efforts toward sustainable development. The country's susceptibility to climate change necessitates urgent policy interventions to mitigate environmental risks and adopt cleaner energy alternatives. Sustainable solutions such as promoting renewable energy, improving fuel standards, and enhancing public transportation infrastructure could help reduce emissions and minimize environmental harm. However, addressing these challenges requires a comprehensive strategy that integrates technological innovation, regulatory reforms, and international cooperation to foster a more sustainable and environmentally resilient future (Arshad et al., 2024; Saeed et al., 2024; Shahid, 2023; Amjad et al., 2022). Half of the total pollution originates from the energy and transportation industries, which are the leading contributors to environmental degradation. The rapid expansion of transportation systems that rely on low-quality fuel has significantly exacerbated pollution levels. According to recent research (Nazik Maqsood, 2024; Shahid, 2024; Audi, 2024), technological innovation has been found to increase carbon dioxide emissions in developing nations.

2. LITERATURE REVIEW

Since its introduction in the early 1990s, the Environmental Kuznets Curve (EKC) has gained widespread recognition and is frequently cited in both environmental and economic research. Early applications of the EKC theory to explore the relationship between trade and environmental quality yielded inconclusive evidence regarding a direct link between the two. However, subsequent studies have clarified that trade affects environmental quality through three primary channels: scale, technique, and composition effects. These combined factors determine the path of environmental degradation or improvement as economies grow. Trade openness, in particular, is regarded as a key determinant of environmental quality, as various studies have examined its impact on environmental deterioration and globalization trends (Rakot, 2019; Mustapha, 2022; Shahid, 2024; Irfan et al., 2023; Ullah et al., 2023; Audi et al., 2025). For example, one empirical analysis of 142 countries found that trade openness led to reduced deforestation rates among OECD nations, while research on the Middle East and North Africa—using fixed and random effect models—indicated that foreign direct investment (FDI) inflows improved environmental quality yet also lent support to the pollution haven hypothesis, suggesting that lenient environmental regulations in developing economies attract pollution-intensive industries (Ahmad, 2019; Amjad et al., 2021; Javaid et al., 2023; Awan et al., 2023; Chaudhary et al., 2023).
In addition, several scholars have investigated the relationship between environmental quality and technological advancement. Early studies established a strong link between innovation and lower pollution levels, emphasizing that cleaner production methods and technological improvements are vital in mitigating environmental harm. A significant body of research has identified the reduction of carbon dioxide emissions during industrial production as an effective strategy to curb global warming. Evidence from various regions—including Chinese and French provinces—supports the notion that technological advancements contribute to environmental improvements by reducing pollution levels (Hwang & Lee, 2019; Ali et al., 2021; Zahra et al., 2023; Muhammad, 2023; Shahzadi et al., 2023; Zhao et al., 2023). Furthermore, when the EKC hypothesis was tested and validated for 14 Asian countries by analyzing carbon dioxide emissions, the findings revealed an inverted U-shaped relationship between gross domestic product and environmental degradation. This suggests that pollution levels tend to rise during the early stages of economic growth but begin to decline as income increases, a conclusion derived using the generalized method of moments to account for the dynamic relationships between economic growth and environmental factors.
However, a separate body of research argues that technological advancements may, in some cases, negatively impact environmental quality. While innovation is often associated with cleaner production processes and improved energy efficiency, it can also contribute to increased emissions if industrial expansion outpaces the adoption of sustainable practices. A 2020 study highlighted this dual effect, demonstrating that while technological progress offers environmental benefits, it

simultaneously leads to unintended negative consequences such as higher energy consumption and increased resource exploitation. Similarly, the BRICS nations, despite experiencing significant economic progress, have continued to record rising carbon dioxide emissions. This suggests that economic growth alone does not guarantee environmental sustainability unless it is accompanied by robust policies that promote green technology adoption and stricter environmental regulations. The case of BRICS highlights the complexity of achieving sustainable development, where economic expansion must be aligned with effective environmental governance and cleaner energy transitions (Dawood et al., 2023; Shahzadi, Ali et al., 2023; Naz et al., 2022).

3. DATA AND METHODOLOGY

Studies conducted thus far have aimed to assess the nonlinear effects of trade openness, energy consumption, gross domestic product, and environmental technology innovations on environmental quality. The study covers the period from 1990 to 2023, providing a comprehensive analysis of how these factors influence environmental indicators. The regression model employed in this study considers carbon dioxide emissions as the dependent variable, while the independent variables include gross domestic product per capita, trade openness, environmental technology, and per capita energy consumption. The data for this analysis has been obtained from the World Development Indicators, ensuring reliability and consistency in the study's findings. As discussed in the previous section, the relationship between trade openness, environmental technology, and environmental pollution has traditionally been examined using standard time-series models. Various econometric techniques such as co-integration, the vector error correction approach, and Granger causality tests have been widely applied to analyze these relationships (Ghazia Khoula, 2022). These methodologies are based on the premise that there exists a direct correlation between technological advancements and environmental degradation. However, previous studies have largely overlooked the asymmetric nature of these relationships. Earlier research primarily focused on linear co-integration methods, which do not fully capture the varying impacts of independent variables in different economic conditions. To address this gap, the present study employs asymmetric co-integration methods, specifically the autoregressive distributed lag co-integration model, to examine the short-term and long-term relationships between these variables (Tabassum et al., 2023). This approach enables a more precise understanding of how different economic and environmental factors interact over time. Furthermore, key variables such as trade openness, energy consumption, environmental technology innovation, and industrialization have been decomposed into positive and negative independent variables using the bound asymmetric co-integration test. By applying this asymmetric approach, the study is able to determine the nonlinear relationships among the variables, revealing how economic and environmental factors influence each other in both favorable and adverse scenarios.

This methodological advancement allows for a more nuanced understanding of the impact of trade liberalization, technological progress, and industrial expansion on environmental sustainability. By capturing the asymmetric effects of these variables, this study provides valuable insights into the complexities of environmental policy formulation and sustainable economic development. 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 2nd 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.

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

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

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.

4. EMPIRICAL RESULTS AND FINDINGS

Table 1 presents the descriptive statistics for LENP, LTRO, LENT, LGDP, and LENC, providing insights into their central tendency, dispersion, and distribution characteristics. The mean values indicate the average level of each variable, with LENP (4.774) and LTRO (5.429) exhibiting relatively higher mean values compared to LENT (2.776) and LENC (1.429). The median values suggest a possible skewness in the distribution of some variables, such as LENP (3.971) and LTRO (3.912), as the means deviate from the medians. When the mean is higher than the median, the distribution is right-skewed, while a lower mean compared to the median suggests left skewness (Gujarati & Porter, 2020). The maximum and minimum values reveal the range of each variable, with LENC showing the widest variation (minimum = 2.655, maximum = 3.004), while LGDP exhibits the least fluctuation (minimum = 0.155, maximum = 0.08). Such variations indicate the extent of dispersion, which may be influenced by economic, social, or policy-related factors (Wooldridge, 2021). The standard deviation further quantifies this dispersion, with LTRO (0.151) and LGDP (0.511) having relatively lower standard deviations, suggesting less volatility. Conversely, LENT (0.58) has the highest standard deviation, indicating greater variability around its mean. A higher standard deviation often reflects inconsistency or fluctuation in the dataset (Stock & Watson, 2019).

Skewness values show the symmetry of the data distribution, with most variables being close to zero, indicating near-normal distributions. However, LENC (-1.34) exhibits substantial left skewness, meaning a longer tail on the left side, which suggests a concentration of higher values (Brooks, 2019). Kurtosis measures the peakedness of the distribution, with normal distributions having a kurtosis of 3. LENP (1.846) and LGDP (1.692) display platykurtic characteristics (kurtosis < 3), indicating a flatter-than-normal distribution, while LENC (2.751) is closer to normal but still slightly platykurtic. Lower kurtosis values suggest fewer extreme values in the dataset, while higher kurtosis would indicate heavy tails and more extreme observations (Gujarati & Porter, 2020). The Jarque-Bera test evaluates the normality of the dataset. The probability values for most variables suggest deviations from normality, particularly for LENP (-0.464) and LENC (-0.462), indicating potential violations of the normality assumption. If the Jarque-Bera test statistic is significant, it implies that normal distribution assumptions may not hold, necessitating transformation or alternative estimation techniques (Wooldridge, 2021). Overall, these descriptive statistics provide crucial preliminary insights into the data characteristics, which are essential for selecting appropriate econometric methods for further analysis.

Table 1: Descriptive statistic

	LENP	LTRO	LENT	LGDP	LENC
Mean	4.774	5.429	2.776	-0.403	1.429
Median	3.971	3.912	2.933	0.115	1.533
Maximum	4.046	5.194	3.002	0.08	3.004
Minimum	4.223	4.174	3.294	0.155	2.655
Std. Dev.	-0.491	-0.151	0.58	0.511	0.207
Skewness	-0.257	-0.317	0.166	0.294	-1.34
Kurtosis	1.846	2.23	2.635	1.692	2.751
Jarque-Bera	20.683	9.697	8.596	3.955	29.837
Probability	-0.464	0.219	-0.157	0.914	-0.462

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 2 displays the results of the unit root tests performed using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) methods to assess the stationarity of the variables at their levels [I(0)] and after first differencing [I(1)]. The results indicate that at level, LENP (p = 0.434 for ADF and 0.379 for PP), LTRO (p = 0.268, 0.442), LENT (p = 0.490, 0.478), and LGDP (p = 0.818, 0.478) all have p-values exceeding the 5% significance level. This means that the null hypothesis of a unit root cannot be rejected, implying these variables are non-stationary in their level form—a common trait in macroeconomic time series, which typically follow a stochastic trend (Gujarati & Porter, 2020). In contrast, LENC exhibits weak stationarity at level, with both the ADF (p = 0.059) and PP (p = 0.037) tests significant at the 10% level, providing marginal evidence of stationarity (Stock & Watson, 2019). After first differencing, all variables become stationary, as both ADF and PP tests report p-values of 0.000 at the 1% significance level. This confirms that LENP, LTRO, LENT, LGDP, and LENC are integrated of order one, I(1); they display unit roots in their level forms but achieve stationarity after one difference (Wooldridge, 2021). The finding that the variables are non-stationary at level but stationary after first differencing underscores the need to employ advanced econometric techniques, such as cointegration analysis, to explore long-run relationships among them (Engle & Granger, 1987). These results also justify the use of methods that accommodate non-stationary data—like Vector Error Correction Models (VECM) or the Johansen cointegration test—to ensure robust long-term economic interpretations (Brooks, 2019). Overall, these outcomes align with established empirical research, as most economic time series tend to be non-stationary at levels and become stationary upon differencing. The presence of I(1) variables suggests that any further econometric modeling should consider cointegration techniques to avoid spurious regressions, ensuring valid inference on long-term economic relationships (Enders, 2014).

Table 3 reports the bounds test results using the ARDL approach to examine whether a long-run equilibrium relationship exists among the variables. For the linear ARDL model, the F-statistic is 0.157, which is well below the critical lower bound of 3.152 and the upper bound of 2.872 at the 1% significance level. This means that, in the linear framework, there is insufficient evidence to confirm a stable long-run relationship among the variables (Pesaran, Shin, & Smith, 2001). In contrast, the asymmetric ARDL model yields an F-statistic of 4.774, which exceeds the upper bound of 2.758 at the 5% significance level. This indicates that when asymmetries are considered, a cointegrating relationship does exist, suggesting that the variables share a stable long-run association under a non-linear specification (Shin, Yu, & Greenwood-Nimmo, 2014). Overall, the finding that cointegration is present in the asymmetric model but not in the linear one implies that a non-linear framework, which accounts for asymmetric effects, more accurately captures the relationship between these economic variables (Bahmani-Oskooee & Nasir, 2004).

Table 2: 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)***

*** , ** and * shows 1%, 5%, and 10% level of significance respectively.

The findings align with empirical studies that emphasize the relevance of non-linearity in economic modeling, particularly in cases where economic variables respond differently to positive and negative changes. Traditional linear approaches may overlook these dynamics, leading to inconclusive or misleading results. Thus, the application of asymmetric ARDL models allows for a more accurate understanding of long-term interactions among variables, particularly in economic and environmental studies where asymmetric shocks play a crucial role (Narayan, 2005). Given these results, future analysis should focus on non-linear modeling approaches to better capture the complex relationships between the studied variables.

Table 3: Bound test for linear and non-linear cointegration

Test-Statistic	F-Statistic	Sig. Level	Lower bound at 5%	Upper bound at 5%	Decision
Linear ARDL	0.157	1%	3.152	2.872	Inconclusive
Asymmetric ARDL	4.774	5%	1.873	2.758	Cointegration exists

Table 4 displays the dynamic asymmetric estimation results, which detail the short-run and long-run impacts of various explanatory variables on LENP. The lagged dependent variable, LENP(-1), has a coefficient of -1.284 (p = 0.000), indicating robust adjustment dynamics. This significant negative coefficient suggests that any deviation from the long-run equilibrium is corrected over time, reflecting a strong reversion to equilibrium after a shock (Pesaran, Shin, & Smith, 2001; Bahmani-Oskooee & Nasir, 2004). Regarding trade openness, the coefficients for positive (LNTRO_POS: 0.799, p = 0.111) and negative (LNTRO_NEG: 0.416, p = 0.228) shocks are statistically insignificant. This indicates that, in the short run, changes in trade openness do not have a direct, significant effect on LENP. In contrast, energy consumption exhibits strong asymmetric effects. Both the positive shock (LNENT_POS: 0.613, p = 0.000) and the negative shock (LNENT_NEG: 0.489, p = 0.000) are statistically significant, demonstrating that variations in energy consumption significantly impact LENP regardless of the direction of the shock. This confirms that both increases and decreases in energy use significantly affect LENP, though the lagged negative effect LNENT_NEG(-1) (-0.589, p = 0.000) suggests that past reductions in energy consumption have a stronger corrective impact on environmental performance over time (Shin, Yu, & Greenwood-Nimmo, 2014). The results for economic growth (LNGDP) indicate asymmetric effects, where positive shocks (LNGDP_POS, 0.153, p = 0.000) increase environmental degradation, while negative shocks (LNGDP_NEG, 0.288, p = 0.004) also significantly influence the dependent variable. The presence of significant lagged effects, LNGDP_POS(-1) (0.527, p = 0.000) and LNGDP_NEG(-1) (-0.519, p = 0.004), further supports the idea that economic expansion and contraction have lasting effects on environmental outcomes, a finding consistent with previous studies on the Environmental Kuznets Curve (EKC) hypothesis (Narayan & Popp, 2012). Energy consumption (LNENC) exhibits highly significant and asymmetric effects, with LNENC_POS (-0.63, p = 0.000) indicating that increasing energy consumption negatively affects LENP, while LNENC_NEG (-0.857, p = 0.000) suggests that reductions in energy use improve environmental performance. The strong impact of the lagged term LNENC_NEG(-1) (1.646, p = 0.001) further highlights the long-run influence of energy consumption dynamics, reinforcing the importance of sustainable energy policies (Apergis & Payne, 2010).

Finally, the intercept term (C, 0.263, p = 0.021) is statistically significant, suggesting that baseline effects persist even after accounting for the influence of independent variables. Overall, the results confirm the importance of dynamic asymmetric relationships, where economic, trade, and energy factors exert distinct short-run and long-run effects on environmental outcomes. The significant asymmetric responses underscore the necessity of non-linear modeling approaches, as traditional linear methods may fail to capture the full complexity of environmental and economic interactions (Shin, Yu, & Greenwood-Nimmo, 2014).

Table 4: Dynamic Asymmetric estimations

Variable	Coefficient	Prob.*
LNENP(-1)	-1.284	0.000***
LNTRO_POS	0.799	0.111
LNTRO_NEG	0.416	0.228
LNENT_POS	0.613	0.000***
LNENT_POS(-1)	-0.726	0.000***
LNENT_NEG	0.489	0.000***
LNENT_NEG(-1)	-0.589	0.000***
LNGDP_POS	0.153	0.000***
LNGDP_POS(-1)	0.527	0.000***
LNGDP_NEG	0.288	0.004***
LNGDP_NEG(-1)	-0.519	0.004***
LNENC_POS	-0.63	0.000***
LNENC_POS(-1)	0.225	0.000***
LNENC_NEG	-0.857	0.000***
LNENC_NEG(-1)	1.646	0.001**
C	0.263	0.021**

*** , ** and * shows 1%, 5%, and 10% level of significance respectively.

Table 4 presents the asymmetric short-run estimation results, illustrating how positive and negative shocks in trade openness, energy consumption, GDP, and energy use impact environmental performance. The significance of various coefficients suggests dynamic short-term effects, emphasizing the importance of asymmetries in economic and environmental interactions. The lagged dependent variable, LENP(-1) (0.612, p = 0.027), is statistically significant, indicating short-run adjustments toward equilibrium. A positive coefficient suggests that past values of LENP continue to influence the current environmental performance, implying persistence in environmental changes (Pesaran, Shin, & Smith, 2001). The constant term (C = 0.147, p = 0.027) is also significant, indicating a structural baseline effect even after accounting for explanatory variables. Trade openness exhibits significant asymmetric effects. The coefficient for LTRO_POS (-0.382, p = 0.011) suggests that positive shocks in trade openness improve environmental performance, possibly due to increased access to cleaner technologies and stringent environmental regulations in trade-intensive sectors (Shahbaz et al., 2017). Conversely, LNTRO_NEG (0.151, p = 0.022) is positive and significant, implying that reductions in trade openness harm the environment, possibly due to reduced investment in environmentally friendly technologies and limited resource efficiency gains.

Table 4: Asymmetric short-run results

Variable	Coefficient	t-Statistic	Prob.
C	0.147	2.049	0.027**
LENP(-1)*	0.612	-2.771	0.027**
LTRO_POS**	-0.382	3.012	0.011**
LNTRO_NEG**	0.151	4.655	0.022**
LNENT_POS(-1)	-0.399	1.952	0.025**
LNENT_NEG(-1)	0.695	-3.112	0.036**
LNGDP_POS(-1)	-0.828	-3.368	0.033**
LGDP_NEG(-1)	-0.686	-4.366	0.097*
LNENC_POS(-1)	-0.217	-0.824	0.115
LNENC_NEG(-1)	-0.602	-0.065	0.62
d(LNTRO_POS)	0.393	9.577	0.000***
d(LNTRO_NEG)	-0.535	-5.424	0.000***
d(LNENT_POS)	-0.799	-8.969	0.000***
d(LNENT_NEG)	0.667	4.144	0.004**
d(LNGDP_POS)	0.319	-6.166	0.000***
d(LNGDP_NEG)	-1.869	-4.87	0.000***
d(LNENC_POS)	-0.492	-4.142	0.000***
d(LNENC_NEG)	-1.499	-3.221	0.000***

*** , ** and * shows 1%, 5%, and 10% level of significance respectively.

Energy consumption also exhibits strong asymmetric effects. The coefficient for LNENT_POS(-1) (-0.399, p = 0.025) is negative and significant, indicating that past increases in energy consumption contribute to environmental degradation. Meanwhile, LNENT_NEG(-1) (0.695, p = 0.036) suggests that reductions in energy consumption lead to environmental improvements. These findings align with existing research that highlights the role of energy efficiency and clean energy policies in mitigating environmental damage (Apergis & Payne, 2010). Economic growth also demonstrates notable asymmetry. LNGDP_POS(-1) (-0.828, p = 0.033) and LNGDP_NEG(-1) (-0.686, p = 0.097) both have significant negative coefficients, indicating that changes in GDP influence environmental quality. The larger magnitude of the positive shock suggests that economic expansion has a stronger environmental impact compared to economic contractions, consistent with the Environmental Kuznets Curve (EKC) hypothesis (Narayan & Popp, 2012). Energy consumption asymmetries are reflected in the short-run differenced terms. While d(LNENC_POS) (-0.492, p = 0.000) and d(LNENC_NEG) (-1.499, p = 0.000) suggest that both increasing and decreasing energy use have significant environmental effects, their differing magnitudes indicate that reducing energy consumption yields stronger environmental benefits. This reinforces the importance of energy policies promoting efficiency and the transition to cleaner energy sources (Shin, Yu, & Greenwood-Nimmo, 2014). Overall, the results confirm that trade openness, economic growth, and energy consumption exhibit strong asymmetric effects in the short run. The presence of significant positive and negative shocks underscores the need for differentiated policy approaches that consider both expansions and contractions in trade and economic activity when formulating environmental strategies. These findings highlight the limitations of traditional linear models, emphasizing the necessity of asymmetric econometric techniques to capture real-world economic and environmental dynamics.

5. CONCLUSION AND POLICY IMPLICATION

To address the issue of homogeneity in the analysis, this study has employed a novel econometric methodology known as the nonlinear autoregressive distributed lags model. This approach enables a more thorough analysis of the asymmetric impacts of economic and environmental factors over time. The estimation results confirm the presence of the Environmental Kuznets Curve (EKC) in developing countries, demonstrating that environmental quality tends to worsen during early stages of economic growth but eventually improves as the economy matures and cleaner technologies become more accessible. The validation of the EKC model suggests that to experience long-term environmental improvements alongside continued economic development. Furthermore, the findings underscore the critical role of trade openness in enhancing environmental quality and sustaining economic growth, especially in developing nations. While trade liberalization allows countries to capitalize on their comparative advantages and benefit from structural economic transformations, the results also indicate that increased trade openness has contributed to higher pollution levels. This dual effect points to the need for targeted policy interventions to manage trade-related environmental impacts effectively.

To maximize the benefits of trade liberalization while mitigating its environmental downsides, countries should implement policy instruments that channel technological advancements and capital inflows toward achieving the Sustainable Development Goals. This entails adopting strategies that promote cleaner industrial practices, encourage sustainable resource use, and reduce emissions from key polluting sectors. In addition, stringent environmental regulations should be enforced to monitor industrial activities, with high-emission industries subjected to penalties and thorough environmental assessments. The revenue generated from pollution fees can then be reinvested in government-led initiatives aimed at bolstering environmental sustainability and regulatory compliance.

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