



ENVIRONMENTAL SUSTAINABILITY: INVESTIGATING THE ROLES OF FINANCIAL DEVELOPMENT, NONRENEWABLE ENERGY, AND TECHNOLOGICAL INNOVATION ON ENVIRONMENTAL QUALITY IN NIGERIA

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Abstract: This study examines the impact of financial development, nonrenewable energy consumption, and technological innovation on environmental sustainability in Nigeria using the Dynamic Autoregressive Distributed Lag (D-ARDL) model. The findings reveal that increased nonrenewable energy consumption exacerbates ecological degradation in the short run but contributes to environmental improvement in the long run. Similarly, financial development exhibits a dual effect, initially intensifying environmental degradation before fostering sustainability. In contrast, technological innovation consistently enhances ecological quality in both the short and long run. Additionally, greater trade openness is found to support ecological sustainability across both time horizons. Based on these insights, the study recommends that the government introduce tax incentives, subsidies, and low-interest loans to encourage businesses and households to invest in renewable energy technologies such as solar, wind, and hydroelectric power. This can be achieved by gradually reducing subsidies for nonrenewable energy sources and reallocating these funds to support renewable energy initiatives. Furthermore, fostering collaboration among the government, private sector, and international organizations is essential

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for financing and implementing large-scale renewable energy projects, ensuring long-term environmental sustainability in Nigeria.

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1. INTRODUCTION

The nexus among nonrenewable energy consumption, financial development, trade openness, and environmental quality has garnered significant attention in both academic and policy-making circles. Nonrenewable energy sources, such as coal, oil, and natural gas, have been the backbone of the global energy supply for decades. However, their extensive use has led to considerable environmental degradation, including air and water pollution, habitat destruction, and, most notably, an increase in greenhouse gas emissions that contribute to climate change (Wang, *et al.* 2023; Sharafat *et al.* 2023). As the world grapples with the dual challenges of sustaining economic growth and mitigating environmental damage, the role of financial development and trade openness becomes increasingly relevant (Qing, *et al.* 2024).

Financial development is capable of influencing environmental quality through several channels; a more developed financial system can facilitate investments in cleaner technologies and renewable energy, potentially reducing environmental harm, while on the other hand, increased industrial activities and energy consumption as a result of financial development without adequate environmental regulations, it can exacerbate environmental degradation (Nathaniel *et al.*, 2024; Parveen, *et al.* 2023). The relationship is thus complex and context-dependent, influenced by the regulatory framework, the types of financial products available, and the overall economic structure (Raihan *et al.* 2024). Furthermore, the extent to which a country is integrated into the global economy, also known as trade openness, has a significant impact on environmental quality (Nathaniel *et al.*, 2024; Raihan *et al.* 2024). Theoretically, trade can lead to environmental benefits by enabling countries to specialize in industries where they have a comparative advantage, potentially reducing the overall environmental footprint. Moreover, the importation of advanced technologies can help lower emissions and improve energy efficiency (Horky & Fidrmuc, 2024). However, trade can also lead to a "race to the bottom" in

environmental standards, where countries might lower regulations to attract foreign investment, leading to greater environmental degradation (Halim, *et al.* 2024).

As one of Africa's largest economies, Nigeria faces significant challenges and opportunities in balancing economic growth with environmental sustainability. The country is heavily reliant on nonrenewable energy sources, particularly oil and natural gas, which constitute a major part of its economy. This dependence on fossil fuels has contributed to substantial environmental degradation, including oil spills, deforestation, and air and water pollution (Rizwanullah *et al.* 2024; Haldar & Sethi 2022). Additionally, the flaring of natural gas, a common practice in Nigeria's oil industry, has made the country one of the largest emitters of greenhouse gases in Africa, exacerbating climate change and environmental deterioration (Baloch, *et al.* 2018)

Financial development in Nigeria has the potential to play a crucial role in shaping environmental outcomes. A more advanced financial sector could mobilize resources for investments in cleaner technologies and renewable energy, supporting a transition toward a more sustainable economy (Baloch, *et al.* 2018). Therefore, as opined by Prempeh (2024), the role of the country's financial sector in environmental quality is influenced by the regulatory environment, the availability of green financial products, and the overall direction of economic development in the country. Trade openness in Nigeria also has significant implications for environmental quality. Nigeria faces risks and opportunities as it continues to integrate into the global economy. Increased trade can lead to environmental benefits through the importation of cleaner technologies and adherence to international environmental standards. However, there is also the risk of environmental harm if trade liberalization leads to increased exploitation of natural resources or if Nigeria becomes a destination for environmentally harmful industries due to weaker regulations (Baloch, *et al.* 2018). Against the above backdrop, exploring the impact of nonrenewable energy consumption, financial development, and trade openness on environmental quality in Nigeria is required from the angle of economic policy uncertainty.

This research makes several contributions to the existing literature. First, to support the ambitious goal of reducing GHG emissions by 20% by 2030 in Nigeria, the study's findings will offer valuable insights into the policy

implications of nonrenewable energy use, financial development, and trade intensity on CO₂ emissions. Second, this study differs from previous research by utilizing the dynamic Autoregressive Distributed Lag (D-ARDL) model developed by Jordan and Phillips (2018). The D-ARDL model is preferred over traditional co-integration tests because relying solely on the conventional ARDL approach, as argued by Inuwa *et al.* (2023), can result in biased or spurious outcomes. Finally, the study's findings will aid in crafting policies aligned with the Sustainable Development Goals (SDGs) of achieving net-zero GHG emissions by 2050 and reinforce the broader objective of fostering a more robust and sustainable environment.

The remainder of the paper is organized as follows: Section 2 reviews the relevant literature; Section 3 discusses the study's detailed methodology, while Section 4 presents the empirical results along with their discussions. Section 5 concludes the paper and outlines the policy implications of the findings.

2. LITERATURE REVIEW

The influence of a well-established financial system, clean energy use, and technological innovation toward achieving the United Nations' SDGs 13 of taking urgent action to combat climate change and its impact is widely acknowledged in both low- and high-income countries (Yadav *et al.*, 2024). In a comprehensive study by Ahmad *et al.* (2024), the impact of energy efficiency, technological innovation, and financial development on carbon dioxide emissions in developing Asian regions was analyzed using the Error Correction Model (ECM) and incorporated the concept of the environmental Kuznets curve (EKC) using data from 1995 to 2021, and the findings indicated that when financial development experiences positive shocks, it aligns with the U-shaped EKC. Whereas, when financial development experiences negative shocks, it results in environment-friendly outcomes. Yadav *et al.* (2024) conducted a panel analysis of BRICS economies to investigate the nexus between financial development, renewable energy utilization, and environmental quality and discovered a positive impact of financial development, and renewable energy utilization on environmental quality. Another finding by Qing *et al.* (2024) revealed that trade openness, real oil prices, and economic development have short-term negative effects on the environment while green energy consumption has a long-term positive impact on environmental sustainability. They used the

Westerlund cointegration test, Augmented Mean Group (AMG) estimator, Pooled Mean Group (PMG), and Dumitrescu and Hurlin (DH) causality test. Ozturk *et al.* (2024) explored the dynamic relationships between ecological footprint, economic performance, financial development, energy usage, and foreign direct investment in South Asian economies utilizing panel data from 1971 to 2018 utilizing the Westerlund cointegration test. The findings support both the environmental Kuznets curve and pollution haven hypotheses for South Asian economies. They further discovered that, financial development increases environmental conservation while energy usage substantially disrupts the ecological sustainability of the selected nations.

As pointed out by Huang (2024), globalization, financial development negatively affect environmental sustainability in the BRICS countries while innovation exerts a positive impact on the environment. They examined the nexus of natural resources, financial development, innovation, globalization, and environmental sustainability in BRICS countries from 1990 to 2021 by employing dynamic system panel data estimations and robust random effect GLS regression for long-run estimates. Bashir *et al.* (2024) established a novel theoretical framework and analyzed the role of energy prices, energy consumption, gold prices, and economic growth on environmental degradation in newly industrialized economies. Utilizing the CS-ARDL econometric approach and AMG, CS-DL, Driscoll-Kraay, and FGLS to enhance the robustness of their findings, their findings revealed that energy resource prices and renewable energy consumption reduce environmental degradation, while gold prices and fossil energy consumption elevate ecological pollutants. They also confirmed the existence of the EKC hypothesis. Another study by Solaimani and Montes (2024) assessed the influences of renewable and non-renewable energy consumption, foreign direct investment, natural resource rents, and good governance on both economic growth and carbon emissions in New Zealand using autoregressive distributed lag method on annual data from 1990 to 2020. The results suggested that the use of renewable energy, financial development, and good governance significantly reduce CO₂ emissions. The exchange rate also contributes to reducing carbon emissions due to its negative impact on economic growth and trade. Also, nonrenewable energy consumption is the major contributor to higher CO₂ emissions.

Employing stepwise regression for model selection, as well as Fully Modified Ordinary Least Squares, Panel Ordinary Least Squares, and Fixed Effects Model, Suleman *et al.* (2024) confirmed the existence of the existence of EKC in emerging economies from 1995 to 2020 after conducting an in-depth analysis of the trade drivers that influence trade openness and their impact on carbon dioxide emissions. Ogboghro and Kelechi Nnaji (2024) assessed the dynamic nexus between financial development and environmental degradation in BRICS and Non-BRICS emerging markets from 2000 to 2022 considering the role of energy consumption, economic growth, trade openness, and foreign direct investment, using a sample of 22 emerging markets and Germany. The study provides evidence that financial development and environmental degradation are cointegrated. Economic growth and energy consumption are found to be the main drivers of environmental degradation in the short run, while financial development, energy efficiency, economic growth foreign direct investment all have a positive effect on environmental degradation in the long run. Whereas, trade openness reduces CO₂ emissions in the long run. OuYang *et al.* (2024) quantified the impacts of economic growth, energy consumption levels, financial development tools, institutional qualities, and globalization on environmental degradation by employing a dynamic panel model and robustness check using quantile regression and generalized moment method approaches. The findings demonstrated that renewable consumption, globalization, and institutional quality significantly reduce the negative impacts on the natural environment across all quantiles, whereas, electricity consumption, economic growth and financial development have a significant negative impact across all quantiles.

A study by Mayanja *et al.* (2024) shed more light on the impact of renewable energy consumption, financial development, trade openness, and environmental quality in Uganda spanning the period 1990-2019 using the Autoregressive Distribution Lag (ARDL). Their Findings showed that renewable energy consumption improves environmental quality both in the short and long run, while trade openness and financial development are negatively related to environmental quality in the short and long run. Bergougui (2024) applied a nonlinear autoregressive distributed lag (NARDL) approach to examine the impact of technological innovation, fossil fuel energy use, and renewable energy on environmental degradation and discovered that

positive shocks in technological innovation decrease ecological degradation, whereas negative shocks increase environmental degradation. Positive shocks in renewable energy use also decrease ecological degradation, while negative shocks have no effect. In contrast, positive shocks in fossil fuel energy use increase ecological degradation, but negative shocks have an even stronger effect, resulting in almost double environmental degradation over time.

Using First pooled mean group (PMG) estimates, Addai *et al.* (2024) evaluated the long-run asymmetric effect of urbanization, energy consumption, and regulatory quality on environmental degradation, and the results suggested short-run asymmetric effects of the urbanization, energy consumption, and regulatory quality on carbon emissions, while the long-run PMG estimates indicate that improvements in regulatory quality reduce carbon dioxide emissions, but increase in both urbanization and fossil energy consumption lead to the corresponding rise in carbon dioxide emissions. Solaymani *et al.* (2024) employed panel vector autoregression method to analyze the interconnection of financial development, renewable energy, and CO₂ emissions across ASEAN nations from 1990 to 2020 discovered that while renewable energy consumption shows an insignificant impact on carbon emissions, financial development, and economic growth significantly and positively influence emissions. Conversely, labor exhibits a notable negative correlation with CO₂ emissions.

This review reveals that numerous studies have investigated the relationship among financial development, renewable and nonrenewable energy consumption, technological innovation, trade, and environmental sustainability, but their findings have been inconsistent. Considering the varied findings from previous studies, further research is necessary to understand this, particularly within the context of the Nigerian economy. This is because investigating the interplay between financial development, energy consumption, technological innovation, trade, and environmental sustainability is crucial for Nigeria, given its status as a major oil producer and emerging market. Understanding these dynamics helps reveal how financial institutions can mobilize investments in renewable energy and green technologies, reducing the adverse impacts of nonrenewable energy use. Furthermore, technological innovation and trade are key drivers of economic transformation that can enhance energy efficiency and foster sustainable practices. This integrated approach provides policymakers

with essential insights to balance economic growth with environmental protection, ultimately ensuring long-term ecological resilience and sustainable development in Nigeria.

3. ECONOMETRIC METHODOLOGY

3.1. Data Sources and Variable Justification

This study uses annual data from 1990 to 2022 for a comprehensive sample of Nigeria for which data is available. Also, the determination of this sample is solely based on data availability, and suitability, and is sufficient enough to carry out robust econometrics analysis based on the Central Limit Theorem, for making key policy suggestions for environmental sustainability. Nigeria is among the world's 10 greatest polluters, emitting 127 million tonnes of carbon dioxide in 2022 (Global Carbon Budget, 2023). CO₂ emissions pose serious problems for the planet since emissions have amplified by more than 100% in the previous three decades (World Bank, 2023).

The study has chosen appropriate variables as follows:

CO₂ emissions are measured in kilotons (kt). This refers to the release of carbon dioxide into the atmosphere, primarily from the burning of fossil fuels such as coal, oil, and gas. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring; nonrenewable energy consumption, which refers to the use of non-renewable energy sources such as coal, oil, and gas to generate electricity, power transportation, and fuel industrial processes; financial development, proxied by domestic credit

Table 1: Data and Sources

Determinants	Code	Sources	Measurement Unit
CO ₂ emissions	CO2	WDI (2023)	kilotons (kt)
nonrenewable energy consumption	NREC	EIA (2023)	Kg of oil equivalent
financial development	FD	WDI (2023)	(% of GDP)
Trade openness	TOP	WDI (2023)	(as a share of GDP)
Ecological Innovation	ECI	OECD(2023)	Patent applications (resident and non-resident)

Notes: WDI symbolizes the World Development Indicators, Organization of Economic Cooperation and Development data, and EIA represents the U.S. Energy Information Administration publication.

Source: Author's construction based on WDI, OECD, and EIA datasets.

to private sector, refers to financial resources provided to the private sector by financial corporations, such as through loans, purchases of nonequity securities, and trade credits and other accounts receivable, that establish a claim for repayment; Trade openness, refers to exports and imports of goods and services (as a share of GDP) and ecological Innovation, which is the total patent applications (residents and non-residents).

3.2. Model Specification

This paper examines the short and long-term connections between NREC, FD, TOP, and CO2 emissions while controlling for the impact of ECI, in Nigeria. Ecological innovation (ECI) helps reduce pollutants, thereby saving energy and promoting the optimal usage of renewable energy (RE) and conventional sources. ECI also enhances green energy capacities, improving the chance of its supply, and meeting prospective energy demand given the ever-increasing need for energy (Zhang *et al.* 2023). A model from the work of Bergougui (2024) was adapted, specified as follows:

$$CO2 = \beta_0 + \beta_1 NREC_t + \beta_2 FD_t + \beta_3 TOP_t + \beta_4 ECI_t + \varepsilon_t \quad (1)$$

Where CO2, NREC, FD, TOP, and ECI represent the CO2 emissions, nonrenewable energy consumption, financial development, trade openness, and ecological innovation, respectively in Nigeria, and ε is the error term which is assumed to be normally distributed.

For estimation, there is a need to log-linearize the model as specified in equation (2) below. This is necessary to minimize fluctuations in the data and to streamline the scales of the variables.

$$\ln CO2 = \beta_0 + \beta_1 \ln NREC_t + \beta_2 \ln FD_t + \beta_3 \ln TOP_t + \beta_4 \ln ECI_t + \varepsilon_t \quad (2)$$

3.3. Estimation Procedure

3.3.1. Unit Root Inspection

In the first place, before estimating the dynamic ARDL model, numerous unit root tests, such as the Augmented Dickey-Fuller (ADF), the Phillips-Perron (PP), and the Kwiatkowski, Phillips, Schmidt, and Shin (KPSS) were utilized to ensure the stationarity of the data. In addition to the conventional unit root tests employed, this study also utilized Lee and Strazicich's (2013)

unit root test to address the shortcomings of the conventional unit root tests. The Lee and Strazicich, (2013) unit root test is a two-structural-break minimal Lagrange multiplier (LM) unit root test. In comparison to previous structural break tests, such as the Clemente *et al.* (1998), Lumsdaine and Papell (1997), and Zivot and Andrews (1992) tests, the Lee and Strazicich test has superior size and strength features, as well as the ability to determine break dates more reliably. As a result, using the Lee and Strazicich test removes the threat of wrong calculations and break date forecasts (Zhang *et al.* 2023).

3.3.2. Cointegration Assessment Using ARDL bounds test

This study employed the Autoregressive Distributed Lag (A-ARDL) bounds testing approach to the cointegration developed by Peseran *et al.* (2001) to assess the impact of nonrenewable energy consumption, financial development, trade openness, and ecological innovation, on CO2 emissions in Nigeria, because of its superiority over other cointegrating techniques such as the cointegration approaches developed by Engle and Granger (1987), Johansen (1988), and Søren Johansen (1990), which are not appropriate when the data series has a mixed order of integration. In contrast, when data series lack a specific sequence of integration, the ARDL model is more versatile in terms of application, like, when the variables are of different integration orders, including I(0) and I(1), but, inadequate if any of the variables is I(2). It could also be applied systematically to a small dataset to generate reliable estimates, gives additional prospects, and is apt to cope with any endogeneity issues that may occur in variables (Zhang *et al.* 2023).

The model is described in the following manner:

$$\Delta \ln CO2_t = \delta_1 + \sum_{j=1}^q \beta_1 \Delta \ln CO2_{t-j} + \sum_{j=0}^{K_2} \beta_1 \Delta \ln NREC_{t-j} + \sum_{j=0}^{K_3} \beta_2 \Delta \ln FD_{t-j} + \sum_{j=0}^{K_4} \beta_3 \Delta \ln TOP_{t-j} + \sum_{j=0}^{K_4} \beta_4 \Delta ECI_{t-j} + \alpha_1 \ln CO2_{t-1} + \alpha_2 NREC_{t-1} + \alpha_3 \ln FD_{t-1} + \alpha_4 \ln TOP_{t-1} + \alpha_5 ECI_{t-1} + \sigma D_t + \mu_t \dots \dots \dots (3)$$

where μ_t represents the error term and Δ_t symbolises the first difference. While β_i reflects short-run dynamics, and α_i for long-run events. D_t is appended to the dataset to accommodate for any structural changes. Here, the H_0 is $\alpha_1 = \alpha_2 = 0$, suggesting that there is no long-run relationship among the variables.

The error correction model (ECM) for evaluating short-run features is specified as:

$$\Delta \ln CO_{2t} = \delta_1 + \sum_{l=1}^q \beta_1 \Delta \ln CO_{2t-l} + \sum_{l=0}^{K_2} \beta_1 \Delta \ln NREC_{t-l} + \sum_{l=0}^{K_3} \beta_2 \Delta \ln FD_{t-l} + \sum_{l=0}^{K_4} \beta_3 \Delta \ln TOP_{t-l} + \sum_{l=0}^{K_4} \beta_4 \Delta ECI_{t-l} + \lambda ECT + \mu_t \quad (4)$$

Where β_i denotes short-run coefficients, ECT is the error correction term that measures the speed at which each period returns to equilibrium following a shock. The expected value of the ECT parameter is between -1 and 0, with 0 indicating no divergence toward equilibrium and 1 representing perfect convergence, implying that if the value is -1, any shock in the given period is properly adjusted in the following period.

3.4. Dynamic Autoregressive Distributed Lag Model

To overcome the limitations of the classical ARDL model, this study utilized the Dynamic Autoregressive Distributed Lag (D-ARDL) model, as propounded by Jordan and Philips (2018). This estimator is particularly effective in plotting graphs to predict both positive and negative changes in examining the interconnected short-term and long-term relationships among the variables of the study, improving accuracy, and addressing the complexities associated with the conventional ARDL method (Udeagha & Ngepah, 2022), in addition to its applicability regardless of the order of integration of the variables, except for I(2) (Inuwa *et al.*, 2024). The D-ARDL estimator is expressed in equation (8):

$$\Delta \ln CO_{2t} = \alpha_0 + \alpha_0 \ln CO_{2t-1} + \rho_1 \Delta \ln NREC_t + \phi_1 \ln NREC_{t-1} + \rho_2 \Delta FD_t + \phi_2 FD_{t-1} + \rho_3 \Delta \ln TOP_t + \phi_3 \ln TOP_{t-1} + \rho_4 \Delta ECI_t + \phi_4 ECI_{t-1} + \delta ECT_{t-1} + \mu_t \quad (8)$$

Here, error correction term (ECT) represents the adjustment factor, which must be negative and significant to ensure convergence in the time series. Post-estimation diagnostics included the Breusch-Godfrey test to assess autocorrelation, the WHITE test to identify heteroscedasticity, the Ramsey RESET test to evaluate model specification, and the Jarque-Bera test to analyze the distribution of errors. Additionally, the CUSUM and CUSUMQ tests were utilized to evaluate the model's stability.

3.4.1. Robust Analysis

To guarantee robustness, this study employed both Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) models to explore the relationship between the dependent and independent variables. FMOLS and DOLS estimators are recognized for their unbiased properties, efficient management of normalization asymptotics, and their role as optimal estimators in cointegration regressions. These models refine ordinary least squares (OLS) to address problems such as serial correlation and endogeneity in regressors, which occur due to long-run relationships (Inuwa *et al.*, 2022).

4. RESULTS AND DISCUSSION OF FINDINGS

4.1. Descriptive Statistics

The summary of the statistical properties of the variables of the study are presented in Table 2. Based on the results obtained, the mean and median values are approximately the same. However, the volatility in the variables is revealed by the standard deviation as it is high in FD compared to CO₂, EXT_D, FDI, and REC.

Table 2: Summary Statistics and Correlation Matrix

Variables	CO ₂	NREC	FD	ECI	TOP
Mean	11.42340	2.958651	19.34710	12.56161	1.370070
Median	11.42744	2.937932	18.87677	8.474576	0.785612
Maximum	11.65108	3.128723	22.84479	40.54054	4.278809
Minimum	11.19504	2.763431	15.85414	0.000000	0.277960
Std. Dev.	0.108181	0.089869	1.750607	12.08046	1.328748
Skewness	-0.109549	0.141877	0.322084	0.913020	1.210212
Kurtosis	2.685426	2.462508	2.372391	2.832811	3.022378
Jarque-Bera	0.153084	0.384807	0.842546	3.502473	6.103079
Probability	0.926314	0.824974	0.656211	0.173559	0.047286
Correlation Matrix					
CO ₂	1.000000				
NREC	0.213337	1.000000			
FD	0.191485	0.998666	1.000000		
ECI	-0.076847	-0.638158	-0.638112	1.000000	
TOP	0.345322	0.143105	0.129619	-0.493123	1.000000

Source: Author's computation

From Table 2, the standard deviation demonstrated higher volatility in ecological innovation, followed by financial development, and trade openness, while CO₂ emissions and trade openness recorded lower volatility. The lower part of Table 2 measures the presence or otherwise of multicollinearity in the model, using the pair-wise correlation matrix, and the results reveal the strength of correlation between a pair of variables. The higher coefficient of correlation ($r \geq 0.8$) shows severe multicollinearity among the variables. The results of the pair-wise correlation matrix statistics indicate the absence of multicollinearity.

4.2. Unit Root Tests

In the empirical investigation of time series modeling, the first important step is the preliminary investigation to reveal the stationary properties of variables through the use of unit root tests. This is because knowing the stationary properties of the variables will provide a guide in making the right choice of estimation techniques to be employed as well as avoiding spurious results. To achieve these, the study utilized the conventional Augmented Dickey-Fuller (ADF) and Phillips Perron (PP) tests, while for the structural break test, Lee and Strazicich LM test was utilized, and the outcomes are displayed in Table 3.

Table 3 Unit root test

Variables	Augmented Dickey-Fuller	Phillips Perron	Lee Strazicich Unit Root Test	
			Break Year	Test Statistics
Level	Test Statistics		Break Year	Test Statistics
LCO2	-2.942633	-2.942633	2006 2012	-6.198956
LNREC	-1.084324	-1.229828	2001 2006	-6.968035
FD	-3.864131**	-2.064151	2003 2017	-5.592286*
ECI	-2.858980	-2.077189	2004 2009	-7.933864***
TOP	-2.441700	-2.629323	2004 2017	-7.145371***
<i>First Difference Critical value (1%, 5%, and 10%)</i>				
LCO2	-5.549099**	-6.484956***	2002 2007	-8.038877***
LNREC	-6.791774***	-4.813348***	1995 2007	-9.628696***
FD	-7.932322***	-6.787627***	2004 2016	-6.937358***
ECI	-5.716410***	-6.588783***	----	---
TOP	-4.909084***	-5.681663***	----	---

***, ** and * show significance at 1, 5 and 10% levels respectively.

Source: Authors' computations

The results from Table 3 reveal that all the variables have unit root at their level values when tested with intercept and trend with the exception of FD,

which is stationary at 5%. However, the variables were subjected to the first difference and they became stationary. The results from all the unit root tests showed that the stationary properties of the variables are $I(0)$ and $I(1)$, hence, satisfying the condition for the use of the novel dynamic ARDL cointegration.

4.3. Lag Length for F- F-Bound Cointegration Test

The result of the optimal lag length is presented in Table 5:

Table 5: Lag Length for F-Bound Cointegration Test

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-35.79676	NA	2.81e-05	3.708797	3.956761	3.767210
1	21.00399	82.61929*	1.67e-06	0.817819	2.305604	1.168296
2	42.70199	21.69799	3.45e-06	1.118001	3.845607	1.760543
3	106.8039	34.96469	4.26e-07*	-2.436719*	1.530708*	-1.502113*

*Indicates lag order selected by the criterion

Source: Author's Computations.

The lag order selection by five different criteria is presented in Table 5. All the lag selection criteria, except LR, indicate that a lag length is the optimal lag of three (1) for the F-bound test of cointegration.

4.5. Bound Test for Cointegration

The results of the bound test of cointegration are shown in Table 6.

Table 6: Bound Test for Cointegration

H_0 : No cointegration

F-Statistic	Significance Level	Bound Critical Values		K
		I(0) Bound	I(1) Bound	
4.389090	1%	3.74	5.06	4
	2.5%	3.25	4.49	
	5%	2.86	4.01	
	10%	2.45	3.52	

Source: Author's Compilation using Eviews

Table 6 presents the result of the bound test, where the null hypothesis of no cointegration is rejected because the F- statistics is higher than the upper-bound critical values at 5% level of significance. Therefore, cointegration between the variables under discussion is supported by our empirical results.

4.6. Dynamic ARDL Simulations Model Results

Results from the dynamic ARDL simulation model are shown in Table 7.

Table 6: Dynamic ARDL Simulations Results

<i>Variables</i>	<i>Coefficients</i>	<i>Std. Err</i>	<i>t- Stat</i>	<i>Prob.</i>
<i>D-LNREC</i>	1.314737	.0441663	2.022	0.048
<i>L-LNREC</i>	-.0393872	.0459641	1.77	0.092
<i>D-FD</i>	.003499	.012939	-1.05	0.303
<i>L-FD</i>	-.002299	.0131796	-2.95	0.035
<i>D-ECI</i>	-.0040152	.0038312	2.20	0.041
<i>L-ECI</i>	-.0020345	.00336	2.75	0.036
<i>D-TOP</i>	-.0068921	.4391942	-8.67	0.000
<i>L-TOP</i>	-.0112241	.7625103	-2.33	0.039
<i>Cons</i>	1.848623	5.49248	1.55	0.138
<i>ECT(-1)</i>	-0.222768	0.042785	-5.206638	0.0001
<i>R-squared</i>	0.8636	<i>Adjusted R-squared</i>		0.7759
F-statistics	9 .018699 (0.0001)			
Simulations	5000			

Source: Author's Computation.

Having confirmed the presence of longrun relationship among the study variables, this study employed the novel dynamic ARDL simulations, and the outcomes are presented in Table 6. The results reveal that in the shortrun, nonrenewable energy consumption contributes significantly to rising CO₂ emissions at 5% and an inverse relationship in the longrun at 10% levels of significance respectively. This shows that any 1% increase in nonrenewable energy consumption escalates environmental pollution by 1.31% in the shortrun, and reduces CO₂ emissions by 0.039% in the longrun. This outcome is in line with what Lanhui and Ibrahim (2024) discovered in South Africa and Ganda, (2024) in BRICS countries. Similarly, the coefficient of financial development (FD) promotes environmental damage in the short run and promotes its quality in the long run. This implies that any 1% increase in FD will increase CO₂ emissions by 0.003% in the short run, and reduces it by 0.002% in the long run, corroborating the findings of Ganda, (2024) in BRICS countries and Solaymani and Montes, (2024) in New Zealand. However, Ecological innovation (ECI) in Nigeria positively and significantly promotes environmental quality in both periods at 5% levels of significance. This suggests

that 1% appreciation in ECI promotes environmental quality by 0.004% and 0.002% in the short and long run, respectively. This result is supported by the work of Jó *et al.*, (2024) in the US and Pham and Nguyen (2024) in Thailand. Finally, trade openness significantly reduces CO₂ emissions both in the short run and in the long run. This suggests that an increase in trade openness immediately reduces carbon emissions, thereby promoting environmental quality in Nigeria. 1% appreciation in TOP promotes environmental quality by 0.007% and 0.011% in the short and long run, respectively. These findings are confirmed by the works of Jó *et al.*, (2024) in the US and Bashir *et al.*, (2024) in the newly industrialized countries.

4.4.3. Diagnostic Statistics Tests

The series of diagnostic checks have been employed in the form of normality, serial correlation, heteroscedasticity, and functional misspecification, and the results are displayed in Table 8.

Table 8: Diagnostic statistics tests

<i>Diagnostic Statistics Tests</i>	<i>X² (p Values)</i>	<i>Results</i>
Breusch–Godfrey LM test	0.7823	No serial correlations
Breusch–Pagan–Godfrey test	0.9599	No heteroscedasticity
Ramsey RESET test	0.8343	Model is correctly specified
Jarque–Bera Test	0.1153	Normal estimated residuals

Source: Author's Computations.

As evidenced from the Jarque-Bera test, Breusch-Godfrey serial correlation LM test, and Ramsey RESET test, the estimated model has passed all the post-estimation tests. Similarly, the results of the CUSUM test displayed in Figure 1 suggests the constancy and stability of residuals and models, respectively.

To further visualize the impact of the explanatory variables on the explained variable, this study utilized the impulse response plots generated from the dynamic ARDL simulations, and the figures are depicted in Figure 3–6. The plot displayed in Figure 3 unmask the positive and negative response of NREC and establish stimulating effect on environmental quality in Nigeria. The effect of the increase in NREC demonstrate a reduction on CO₂ emissions in the shortrun and in the longrun, while decrease in NREC raises CO₂ emissions as displayed in Figure 3. Similarly, the rise in financial development

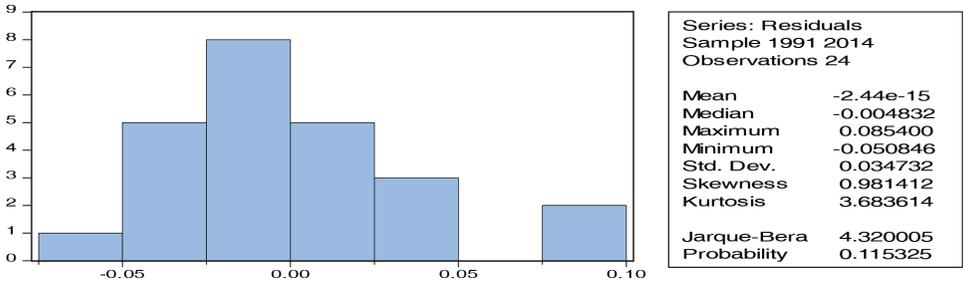


Figure 1: Histogram Normality Test

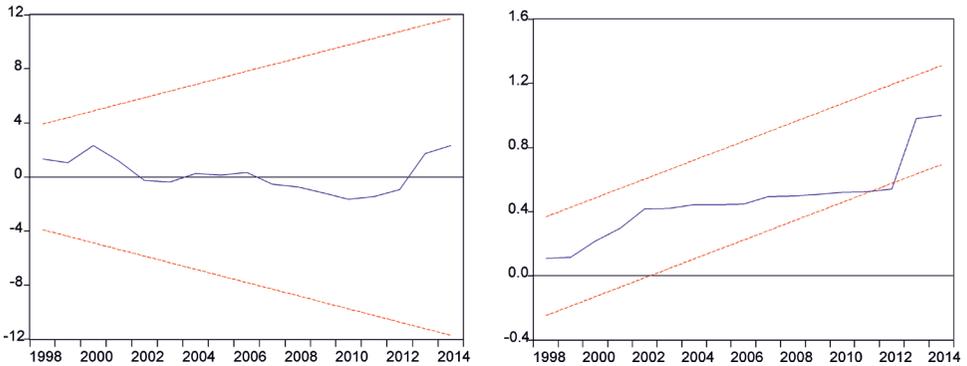


Figure 2: Plot of CUSUM and CUSUMSQ Plots

slows down environmental quality in Nigeria, while its fall raises the quality of the environment as clearly seen in Figure 4. Figure 5 depicts the nexus between ecological innovation (ECI) and CO₂ emissions using an impulse-response plot. The plot depicts the change in ECI and how it impacts environmental quality in Nigeria. A 10% increase in ECI indicates a weak short-term and strong long-term negative impact on CO₂ emissions, while its 10% decrease

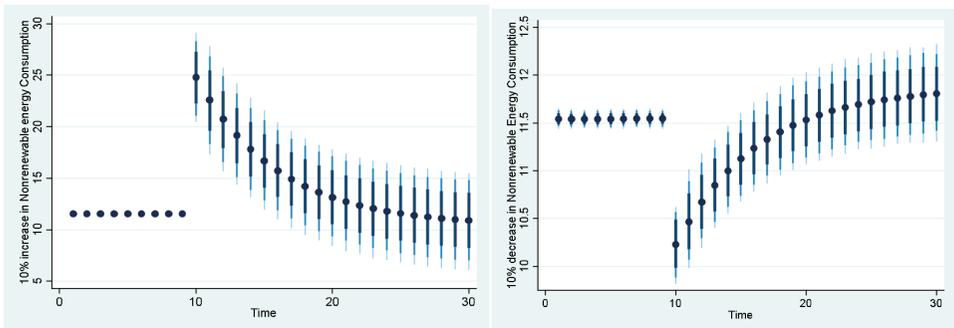


Figure 3: The above figure signifies a 10% increase or decrease NREC and its effect on environmental quality in Nigeria

indicates a positive impact on CO₂ emissions in the shortrun, and longrun. Finally, the rise in trade openness slows down environmental degradation in Nigeria, while its fall raises the environmental degradation as clearly seen in Figure 6.

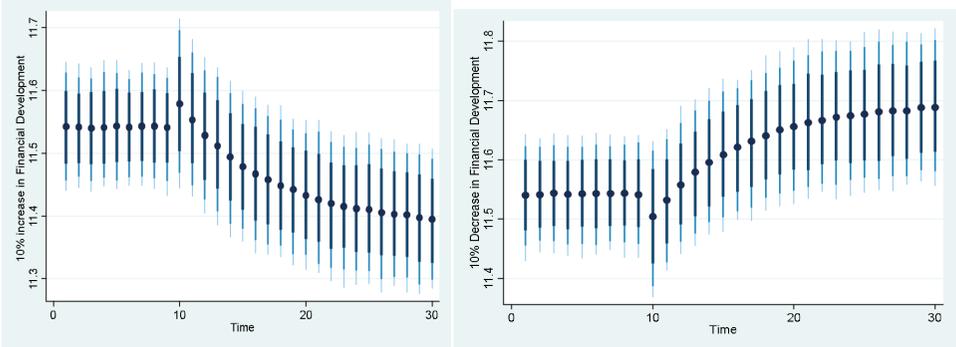


Figure 4: The above figure signifies a 10% increase or decrease FD and its effect on environmental quality in Nigeria

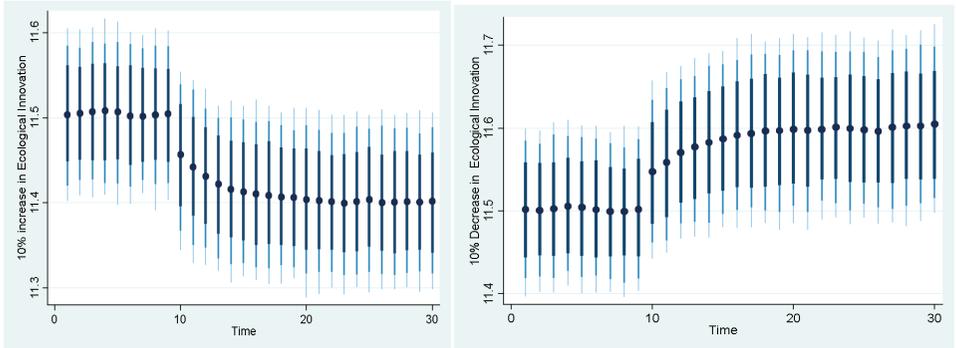


Figure 5: The above figure signifies a 10% increase or decrease ECI and its effect on environmental quality in Nigeria

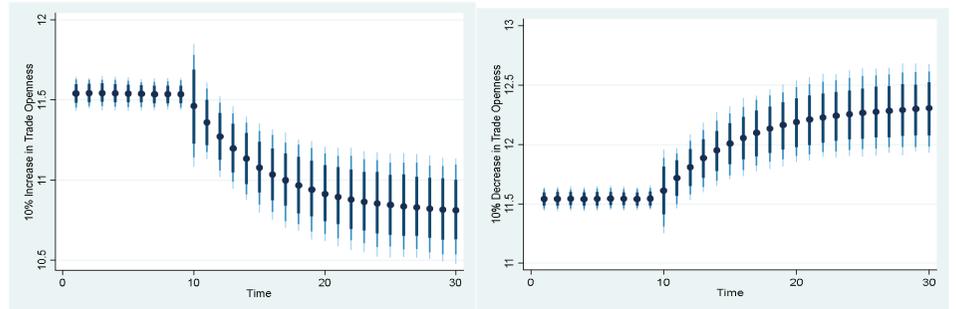


Figure 6: The above figure signifies a 10% increase or decrease ECI and its effect on environmental quality in Nigeria

5. CONCLUSION AND POLICY RECOMMENDATIONS

This work established the empirical impact of nonrenewable energy consumption, financial development, trade openness, and ecological innovation on environmental quality in Nigeria considering time series data from 1990 to 2022, using crucial econometrics estimators including the classical and structural breaks unit root tests, the novel dynamic ARDL simulation model and post estimation techniques. Findings revealed that an increase in nonrenewable energy consumption escalates environmental degradation in the shortrun, while in the longrun it promotes environmental quality in Nigeria. Similarly, a rise in financial development deteriorates environmental sustainability in the shortrun, but in the long run, it promotes environmental quality. However, Ecological innovation raises environmental quality both in the short and long run, respectively. Finally, an increase in trade openness promotes environmental quality both in the short run and long run.

This paper presents important policy recommendations for Nigeria's environmental sustenance based on the outcomes. The study recommends that the government should introduce tax breaks, subsidies, or low-interest loans for businesses and households that invest in renewable energy technologies like solar, wind, or hydroelectric power. This can be achieved through a gradual reduction in subsidies for nonrenewable energy sources, and redirecting those funds to support renewable energy projects and innovations. There is also a need to encourage collaborations among the government, private sector, and international organizations to fund and implement large-scale renewable energy projects. Moreover, there is a need for increased government funding for research and development in ecological innovations, and to facilitate the transfer of green technologies from developed countries to Nigeria through partnerships and international agreements, particularly those tailored to Nigeria's unique environmental challenges. Finally, this research also recommends the implementation of trade policies that encourage the import and export of environmentally friendly goods and services, and establish and enforce strict environmental regulations for imported goods to prevent the inflow of environmentally harmful products. This could include lower tariffs on green technologies and higher tariffs on polluting goods, and make Environmental Impact Assessments (EIAs) obligatory for all major industrial projects, with a particular focus on assessing the impact of nonrenewable energy consumption.

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