RENEWABLE ENERGY ADOPTION AND ENVIRONMENTAL POLLUTION IN NIGERIA: AN EMPIRICAL EVIDENCE

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ABSTRACT
This study investigates the short-run and long-run impacts of renewable energy, energy efficiency, energy equity, and economic growth on environmental pollution (measured by CO_2 emissions) in Nigeria using the Autoregressive Distributed Lag (ARDL) framework. The analysis utilizes annual time series data to examine the dynamic relationships among the variables, with particular emphasis on policy-relevant insights for sustainable development. The results reveal that both renewable energy and energy efficiency significantly reduce environmental pollution in the short and long run, underscoring their crucial role in mitigating climate change. Economic growth also contributes to emission reduction, providing empirical support for the Environmental Kuznets Curve (EKC) hypothesis in the Nigerian context. Conversely, energy equity is positively associated with emissions, indicating that wider energy access without a transition to cleaner energy sources may exacerbate environmental degradation. The study recommends scaling up investment in renewable energy, enforcing energy efficiency standards, ensuring equitable access to clean energy, and adopting green growth policies. These findings offer valuable guidance for policymakers in designing integrated energy and environmental strategies aligned with Nigeria's sustainable development goals.

Keywords: Renewable energy, Energy efficiency, Energy equity, Economic growth, Environmental pollution, ARDL, Nigeria, CO_2 emissions.
JEL Codes: C32, O44, Q42, Q53 and Q56

1. INTRODUCTION
Environmental pollution in Nigeria is a pressing issue with serious consequences for public health, ecosystems, and economic progress. It manifests in multiple forms—air, water, soil, and noise pollution—largely driven by vehicle emissions, industrial activities, and gas flaring in the Niger Delta (World Bank, 2021). These sources contribute to greenhouse gas emissions, declining air quality, and rising respiratory illnesses (Amnesty International, 2018). Water pollution results from oil spills, industrial effluents, and agricultural runoff, harming aquatic life and spreading waterborne diseases like cholera (UNEP, 2011; Okon et al., 2020). Soil contamination from oil leaks, improper waste disposal, and agrochemical use threatens

agricultural productivity (Obire & Amusan, 2003). Noise pollution from urbanization and industry also undermines mental well-being (Ajao et al., 2016).

Nigeria's heavy reliance on oil and gas exploration, weak environmental governance, and poor waste management worsen these problems (UNEP, 2011; Nnaji et al., 2015). Despite abundant renewable energy potential especially solar, hydro, wind, and biomass renewables remain underutilized (IRENA, 2021; Energy Commission of Nigeria, 2015). Solar and small hydro sources are particularly suitable for rural electrification (Federal Ministry of Power, 2017; World Bank, 2020). The 2005 Renewable Energy Master Plan was a significant policy milestone, but pollution continues due to industrialization, rapid urban growth, and limited renewable energy adoption (Olufemi et al., 2019; Akinola & Olukanni, 2020).

Climate change as evident through desertification and flooding further compounds environmental degradation (IPCC, 2019; Oladipo et al., 2020). Empirical evidence from studies like Eze and Chinemeogo (2024), Akinpelumi et al. (2024) and Akomolafe (2024) underscores the role of renewable energy and energy efficiency in reducing emissions and promoting environmental sustainability. More previous studies like Sinha & Shahbaz, (2018) and Dogan & Seker, (2016) also revealed that renewable energy consumption helps reduce environmental pollution. According to the Environmental Kuznets Curve (EKC), environmental degradation initially rises with economic growth but declines after reaching a certain income threshold (Grossman & Krueger, 1995). In developing countries like Nigeria, where fossil fuel dependence and infrastructure limitations persist, understanding the short- and long-term interplay between economic growth, renewable energy, and pollution is essential.

Global frameworks such as the Paris Agreement and the UN Sustainable Development Goals (SDGs) stress the need for clean energy transitions. Nigeria's growing population and rising energy demand make the country's transition particularly urgent. This study aims to explore the impact of renewable energy and economic growth on environmental pollution in Nigeria. This paper aimed to examine the impact of renewable energy and economic growth on environmental pollution. The study addresses the following research questions: Does renewable energy adoption significantly reduce environmental pollution in Nigeria? Does economic growth influence environmental pollution in Nigeria? To achieve these objectives, the paper is structured as follows: Section 2 reviews relevant theoretical and empirical literature. Section 3 presents the methodology, including the model specification and estimation techniques. Section 4 discusses the empirical results, while Section 5 offers conclusions and policy recommendations.

2 LITERATURE REVIEW

2.1 Theoretical Literature

Theories for sustainability and energy transition provide structured ways to understand, analyze, and guide the shift from fossil fuel-dependent systems to sustainable, renewable energy-based systems. These frameworks are essential in identifying the pathways, key drivers, and potential barriers to achieving sustainable energy systems adoption and its impacts on environmental pollution.

One such framework is the circular economy, which focuses on eliminating waste and promoting the continual use of resources (Ellen MacArthur Foundation, 2013). It advocates for reducing, reusing, and recycling materials in a regenerative system rather than following the traditional linear "take, make, dispose" model. In energy systems, this model is relevant through its emphasis on renewable energy technologies, the recycling of materials such as solar panels and batteries, and the development of energy-efficient systems that lessen resource extraction and minimize waste production (Stahel, 2016).

In addition to the circular economy, the energy trilemma offers another critical lens for understanding energy transitions. It identifies three core challenges that energy systems must balance (World Energy Council, 2019): energy security, by ensuring a reliable and affordable energy supply; energy equity, through access to energy for disadvantaged populations; and environmental sustainability, by minimizing the negative impacts of energy production and consumption. The energy trilemma highlights the inherent trade-offs and potential synergies among these three elements. A successful energy transition, therefore, must address all dimensions—ensuring secure, affordable, and environmentally sustainable energy systems while prioritizing equitable access, especially for marginalized communities.

Moreover, while earlier studies have examined the circular economy and the energy trilemma as separate frameworks, this study introduces an integrated sustainability-energy nexus. This integrated framework repositions renewable energy not merely as a technological intervention but as part of a broader systemic transformation. It combines the resource efficiency principles from the circular economy with the balanced socio-economic-environmental objectives outlined in the energy trilemma.

In this integrated model, renewable energy technologies act as circular enablers by decreasing raw material extraction and promoting reuse through strategies like recycling solar panels or repurposing battery storage systems. Environmental sustainability, within this context, is reinterpreted using circular principles to build resilient, low-waste energy systems. This integrated approach is particularly relevant for Nigeria's energy transition, where resource constraints and environmental vulnerability present significant challenges. By merging the principles of the circular economy, which promote efficiency and waste reduction, with the dimensions of the energy trilemma, which strive for balance among energy security, equity, and sustainability, this framework provides a comprehensive strategy for addressing Nigeria's dual challenges of environmental pollution and energy poverty.

2.3 Empirical Literature Review

Several studies emphasize that weak policy structures and governance issues are major barriers to renewable energy development in Nigeria. Adeyanju et al. (2020) highlight policy inconsistency and limited government incentives as primary obstacles. Nwozor et al. (2021) reinforce the need for robust institutional frameworks, while Abe et al. (2024) attribute the slow pace of sustainable energy development to regulatory and governance deficiencies. Similarly, Sobajo (2024) calls for clearer and more effective environmental policies to facilitate renewable energy deployment. Ugwu et al. (2022), in their systematic review, also identify infrastructural and financial challenges tied to weak policy implementation. Eluwa et al. (2022) echo this sentiment, noting that even though green technologies promise energy efficiency, poor implementation slows progress.

Studies recognize the critical role of renewable energy in reducing environmental pollution and combating climate change. Elum and Momodu (2017) advocate for an integrated policy framework to link renewable energy adoption with climate mitigation. Aliyu et al. (2018) present a broader continental view, indicating that Nigeria lags behind peer nations due to inadequate institutional and financial capacities. This gap is supported by Oyedepo (2012), who argues that achieving sustainable energy goals depends heavily on strong policy direction and better funding.

Quantitative studies provide valuable insights into the relationship between renewable energy and environmental outcomes. Eze and Chinemeogo (2024), using the ARDL model, find that population growth increases emissions over time, whereas renewable energy consumption helps reduce them. Akinpelumi et al. (2024) apply the NARDL model to uncover asymmetric effects of financial development, urbanization, and economic growth on CO_2 emissions, lending support to the Environmental Kuznets Curve (EKC) hypothesis. Their findings suggest that pollution increases during early stages of economic growth but declines after surpassing a certain income threshold.

Other studies explore how energy consumption and innovation shape environmental impacts. Aleshinloye and Bariki (2022), through Granger causality analysis, find a unidirectional relationship from electricity consumption to economic growth, implying that energy demand strongly influences environmental outcomes. Adepoju et al. (2020), in their firm-level analysis, observe that green managerial innovations are more common than product or process innovations, pointing to a gap in technical capacity and training. These insights suggest a need for targeted skill development and stronger innovation ecosystems to drive greener production.

Foreign investment is also scrutinized for its environmental implications. Akomolafe (2024) finds that foreign direct investment (FDI) contributes to pollution in African nations with weak environmental governance, including Nigeria. This underscores the importance of enforcing environmental regulations in tandem with investment inflows.

Empirical lessons from international contexts show positive outcomes from strong renewable energy policies. The IEA (2021) reports that countries like Germany and Denmark have successfully reduced their carbon emissions while sustaining economic growth through widespread renewable energy adoption. Similarly, Sovacool et al. (2020), in a global meta-analysis, conclude that renewable energy strategies are aligned with climate change mitigation goals.

On a micro level, Akinyele et al. (2015) show that microgrid solutions are effective in improving rural electrification and reducing dependence on diesel generators, which are harmful to the environment. These decentralized systems offer a viable solution to Nigeria's rural energy deficits and associated environmental damage. At a broader scale, Nyiwul (2017) identifies environmental concerns and economic performance as key motivators for renewable energy development in Sub-Saharan Africa, providing foundational insight into why nations like Nigeria must prioritize cleaner energy alternatives.

2.3.1 Gaps in the Empirical Literature Review

While the existing literature provides valuable insights, several gaps remain: Limited focus on the empirical quantification of the direct impact of renewable energy adoption on specific pollution metrics (e.g., CO_2, levels) in Nigeria. Thus, few studies assess the role of renewable energy systems in reducing pollution with limited integration of socio-economic variables (energy efficiency and energy equity) in explaining renewable energy adoption and its environmental impact.

3. METHODOLOGY

3.1 Theoretical Framework

This study is anchored in the Circular Economy Framework and the Energy Trilemma Framework. The integration of these theories provides a multidimensional understanding of how renewable energy adoption can influence environmental outcomes. The Circular Economy emphasizes waste minimization through reduction, reuse, and recycling, while the Energy Trilemma highlights the interdependence of energy security and environmental sustainability.

Integration of Theoretical Frameworks into the Empirical Analysis

The Circular Economy framework emphasizes reducing waste, reusing resources, and transitioning to renewable and regenerative systems. In this study, the share of renewable energy (RES) serves as a practical indicator of Nigeria's shift toward a circular, low-carbon economy. The Energy Trilemma—energy security, energy equity, and environmental sustainability—provides a structure to evaluate trade-offs and synergies in the energy transition. In the study's models, emissions (MMT) capture the environmental sustainability dimension, while GDP growth (GDPR) represents economic vitality, energy equity (access), and renewable energy share (RES) proxies efforts toward energy security through diversified, domestic energy sources.

3.1 Data Sources:

The study utilized annual secondary data spanning from 1990 to 2022. The data for Renewable Energy Share in Electricity Generation, Emissions (MMT), and GDP Growth Rate were sourced from World Bank Indicators and ACRO TRENDS (for GDP growth data from 1980 to 2022)

3.2 Variables and Measurement

Table 1: Variables and Measurements

Variable	Type	Proxy/Measurement	Source
Environmental Pollution (MMT)	Dependent	CO_2 emissions per capita; AQI	World Bank
Renewable Energy Adoption (RES)	Independent	% of total energy from renewable sources	World Bank
Energy Efficiency (EFF)	Mediator	Energy consumption per unit of GDP	IEA
Energy Equity (EQ)	Moderator	Energy	World Bank
GDP per capita (GDP) growth rate	Control	GDP per capita (constant USD)	World Bank and ACRO TRENDS

3.4 Model Specification (with Theoretical Integration):

This study specifies two functional relationships grounded in the Circular Economy and Energy Trilemma frameworks. The models examine the interaction between renewable energy adoption (RES), emissions (MMT), and economic growth (GDPR):

MMT = *f*(RES, *EFF, EQ*, GDPR) consistent with the *Circular Economy* goal of minimizing waste (emissions) by promotin% of population with access to clean g renewable energy, and the *Energy Trilemma* pillar of environmental sustainability.

The corresponding econometric models are expressed as:

$$MMT = \beta 0 + \beta_1 RES + \beta_2 EFF + \beta_3 EQ + \beta_4 GDPR + Ut \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where:

MMT = Carbon emissions (proxy for environmental pollution), RES = Renewable Energy Share in Electricity Generation (%), *EFF*= Energy Efficiency, *EQ*= Energy Equity, GDPR = GDP Growth Rate, Ut= Error term

To capture both short-run dynamics and long-run equilibrium relationships, the study further transforms the models into a Vector Autoregressive (VAR) framework, recognizing the complex feedback loops suggested by the Energy Trilemma:

$$MMTt = \beta 0 + \beta 1\sum MMTt\text{-}1 + \beta 2\sum RESt\text{-}1 + \beta_2\sum EFF_{t-1} + \beta_3\sum EQ_{t-1} + \beta 3GDPRt\text{-}1 + Ut \ldots .2$$

While the Vector Autoregressive (VAR) model captures dynamic feedback among carbon emissions (MMT), renewable energy share (RES), and economic growth (GDPR), it does not distinguish between short-run dynamics and long-run equilibrium relationships. To address this, the study re-specified the VAR into an Autoregressive Distributed Lag (ARDL) model, which enables simultaneous estimation of short-run effects via differenced terms and long-run relationships through lagged levels.. This enhances the ARDL model's flexibility and suitability for analyzing the Energy Trilemma. The ARDL model is specified as follows:

$$MMT_t = \alpha_0 + \sum\alpha_1\Delta MMT_{t-1} + \sum\alpha_2 \Delta RES_{t-1} + \sum\alpha_3\Delta GDPR_{t-1} + \sum\alpha_4 \Delta EFF + \sum\alpha_5 \Delta EQ + \sum\delta_1\Delta DUMt + l_1RES_{t-1} + l_2GDPR_{t-1} + l_3EFF + \beta\, l_4EQ + l_5DUM_t + U_{1t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .3$$

Where;
$\sum\alpha_1\Delta MMT_{t-1}\ldots++\sum\delta_1\Delta DUMt$ represents Short-run effect of changes of the independent variables while $l_1RES_{t-1}\ldots\ l_3DUM_t$ represents Long-run effect of changes of the independent variables
$\alpha_1,\ \alpha_2,\ \alpha_3.$ and δ_1 are short run coefficients while l_1, l_2, l are long run coefficients.

3.3 A Priori Expectations with Theoretical Justification

Based on theoretical frameworks and empirical evidence, the expected signs of the model coefficients are as follows: Renewable energy share (RES) is expected to reduce environmental pollution (MMT), reflecting the shift from fossil fuels to cleaner energy sources. The effect of GDP growth rate (GDPR) is theoretically mixed, pollution may rise during early development stages but decline at higher income levels due to investments in clean technologies. Energy efficiency (EFF) is anticipated to have a negative effect on pollution by reducing emissions per unit of output. The impact of energy equity (EQ) is uncertain, depending on whether expanded access relies on fossil fuels or renewables. These expectations inform the interpretation of the empirical results.

4. RESULTS AND DISCUSSION ON FINDINGS

4.1 Descriptive Statistics

To assess the characteristics of the variables used in the model, descriptive statistics were computed for all series: MMT (emissions), RES (renewable energy share), EFF (energy efficiency), EQQ (environmental quality index), GDPR (GDP growth rate), and DUM (policy dummy). The summary is presented in Table 1.

Table 1: Descriptive Statistics of Variables (N = 33)

Statistic	MMT	RES	EFF	EQQ	GDPR
Mean	99.63	31.65	7.18	0.477	0.043
Std. Dev.	14.27	9.49	5.27	0.082	0.040
Skewness	0.130	-0.255	1.036	-0.416	0.465
Kurtosis	1.987	1.388	2.330	2.452	3.389
Jarque-Bera	1.503	3.928	6.517	1.364	1.398
Probability	0.472	0.140	0.038	0.506	0.497

Source: Authors' Computation (2025) using E-views 10

The variables generally exhibit moderate dispersion and symmetry, with standard deviations that suggest moderate variability around the mean. MMT, RES, EQQ, and GDPR show near-normal distributions based on skewness, kurtosis, and Jarque-Bera probabilities. In contrast, EFF shows significant right-skewness (1.036) and a Jarque-Bera p-value of 0.038, suggesting deviation from normality. This indicates a potential need for transformation (e.g., log or square root) prior to modeling to stabilize variance and normalize the distribution. Overall, the results support the inclusion of these variables in further econometric modeling, such as ARDL or VAR, after addressing non-normality where applicable.

4.2 Pre-estimation Tests

4.2.1 Unit Root Test

This study employed the Augmented Dickey-Fuller (ADF) test to assess the stationarity of the variables. As shown in Tables 2 and 3, a p-value below 0.05 indicates stationarity. The results in Table 4.3 reveal that all variables are stationary at first difference, except for GDPR, which is stationary at level.

Table 2: **ADF Unit root result**

Augmented Dickey-Fuller (ADF)

	At level	**1st different**	**ADF Results**
MMT	0.4662	0.0000***	I(1)
RES	0.8610	0.0000***	I(1)
EFF	0.9783	0.0002***	I(1)
EQQ	0.2355	0.0001***	I(1)
GDPR	0.0093***		I(0)

Critical values: ***, ** and * at 1%, 5% and 10% respectively

Source: Authors' Computation (2025) using E-views 10

Table 3: **ADF Unit root result (log-transformed)**

Augmented Dickey-Fuller (ADF)

	At level	**1st different**	**ADF Results**
LOG(MMT)	0.3292	0.0000***	I(1)
LOG(RES)	0.8485	0.0000***	I(1)
LOG(EFF)	0.9750	0.0002***	I(1)
LOG(EQQ)	0.0568	0.0006***	I(1)
GDPR	0.0093***		I(0)

Critical values: ***, ** and * at 1%, 5% and 10% respectively

Source: Authors' Computation (2025) using E-views 10

The Augmented Dickey-Fuller (ADF) test results, presented in Tables 2 and 3, were used to assess the stationarity of the study's variables. In Table 2, the raw level data showed that MMT (Emissions), RES (Renewable Energy Share), EFF (Energy Efficiency), and EQQ (Energy Equity, measured as % of population with access to energy) were non-stationary at level (p-values > 0.05) but became stationary after first differencing, indicating they are integrated of order one, I(1). In contrast, GDPR (GDP growth rate) was stationary at level, indicating it is integrated of order zero, I(0). To verify the robustness of these results, the variables were log-transformed and re-tested, as shown in Table 3. The log-transformed variables continued to show non-stationarity at level but became stationary after first differencing, reaffirming their I(1) status. GDPR remained stationary at level. This consistency across both raw and log-transformed data confirms the reliability of the ADF test results.

The mixed order of integration (I(0) and I(1)) justifies the use of the Autoregressive Distributed Lag (ARDL) model, which is well-suited for analyzing variables with different integration orders, and enables the exploration of both short-run and long-run relationships.

4.3 Optimal Lag Length

Table 4 shows the lag lengths given by different lag selection criteria.

Table 4: VAR Lag Order Selection Criteria

Variables: LOG(MMT) LOG(RES) LOG(EFF) LOG(EQQ) GDPR

Lag	**LogL**	**LR**	**FPE**	**AIC**	**SC**	**HQ**
0	116.4292	NA	4.09e-10	-7.428610	-7.195077	-7.353901
1	219.4657	164.8585	2.31e-12	-12.63105	-11.22985*	-12.18279
2	249.5643	38.12482*	1.91e-12	-12.97095	-10.40209	-12.14915
3	289.8908	37.63808	1.07e-12*	-13.99272*	-10.25619	-12.79737*

* indicates lag order selected by the criterion

Source: Authors' Computation (2025) using E-views 10

Where: LR= likelihood Ratio (each test at 5% level), FPE= Final prediction error, AIC= Akaike information criterion, SC= Schwarz information criterion and HQ= Hannan-Quinn information criterion

As shown in Table 4, Lag 3 was selected as the optimal lag length based on the Final Prediction Error (FPE), Akaike Information Criterion (AIC), and Hannan-Quinn (HQ) criteria. Although the Schwarz Criterion (SC) favored Lag 1, it is known for being more conservative due to its stricter penalty on additional lags. Given that FPE, AIC, and HQ prioritize model fit while balancing complexity, Lag 3 is considered the most appropriate choice for this study's model.

ARDL F-Bounds Test

The ARDL F-Bounds test assesses whether a long-run (cointegration) relationship exists among the variables. The null hypothesis assumes no cointegration. If the calculated F-statistic exceeds the upper critical value at the selected significance level, the null is rejected, confirming the presence of a long-run relationship.

Table 5: ARDL Bound Test

F-Bounds Test		**Null Hypothesis: No levels relationship**		
Test Statistic	**Value**	**Signif.**	**I(0)**	**I(1)**
F-statistic	5.405401	10%	2.2	3.09
K	4	5%	2.56	3.49
		2.5%	2.88	3.87
		1%	3.29	4.37

Source: Authors' Computation (2025) using E-views 10

Based on Table 5, the F-statistic of 5.405401 exceeds the upper bound (I(1)) at all significance levels, allowing for the rejection of the null hypothesis of no cointegration. This indicates a long-run relationship between the dependent variable and regressors in the model of this study.

4.4 Estimation Test

To evaluate the impact of renewable energy adoption on environmental pollution in Nigeria, the Autoregressive Distributed Lag (ARDL) model was employed. The ARDL framework is suitable for capturing both short-run dynamics and long-run equilibrium relationships among variables, particularly in small-sample time series data with mixed levels of integration.

4.4.1 Short-Run Dynamics (Error Correction Model)

The estimated short-run results are presented in Table 6, highlighting the immediate effects of changes in renewable energy use, energy efficiency, energy equity, and economic growth on environmental pollution, proxied by emissions (LOG (MMT)).

Table 6: Estimated short Run Results

Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
C	7.068516	1.471082	4.804976	0.0005
LOG(RES(-1))	-0.397139	0.154175	-2.575892	0.0258
LOG(EFF(-1))	-0.334588	0.082144	-4.073183	0.0018
LOG(EQQ(-1))	1.064415	0.372169	2.860036	0.0155
GDPR(-1)	-2.098956	0.713705	-2.940930	0.0134
DLOG(MMT(-1))	0.143856	0.200737	0.716641	0.4885
DLOG(MMT(-2))	-0.381678	0.169023	-2.258141	0.0452

DLOG(RES)	0.244700	0.126202	1.938959	0.0786
DLOG(RES(-1))	1.175083	0.205226	5.725792	0.0001
DLOG(RES(-2))	0.423487	0.243712	1.737653	0.1101
DLOG(EFF)	0.142889	0.113735	1.256338	0.2350
DLOG(EFF(-1))	0.399198	0.168880	2.363792	0.0376
DLOG(EFF(-2))	0.094174	0.087933	1.070974	0.3071
DLOG(EQQ)	-0.429193	0.261361	-1.642148	0.1288
DLOG(EQQ(-1))	-0.878679	0.308138	-2.851577	0.0158
D(GDPR)	-0.643719	0.451201	-1.426679	0.1814
D(GDPR(-1))	2.875750	0.559807	5.137035	0.0003
D(GDPR(-2))	1.445141	0.532013	2.716366	0.0201
ECM	-0.917421	0.258086	-3.554718	0.0045
R-squared	0.960498			
Adjusted R-squared	0.895859			
Durbin-Watson stat	1.949241			

Source: Authors' Computation (2025) using E-views 10

Table 6 presents the short-run dynamics, showing how differenced variables influence emissions. The lagged value of emissions (MMT) has a significant negative impact on current emissions (p = 0.0045), indicating that past emissions help reduce current levels—likely due to policy or technological adjustments. The previous period's renewable energy share has a significant negative effect on emissions (p = 0.0258), suggesting that increasing renewable energy reduces emissions in the short term by displacing fossil fuel use. Similarly, past improvements in energy efficiency significantly lower emissions (p = 0.0018), aligning with expectations that efficiency reduces energy use and pollution.

Interestingly, lagged energy equity (EQQ) is positively associated with emissions (p = 0.0155), implying that expanded access to energy—especially from fossil sources—may increase emissions in the short run. Lagged GDP growth also shows a significant negative relationship with emissions (p = 0.0134), likely reflecting the environmental benefits of economic modernization and cleaner technologies. However, the first difference of emissions (ΔMMT(-1)) is not statistically significant **(**p = 0.4885), suggesting that recent changes in emissions do not immediately influence current emissions. While lagged energy efficiency (ΔLOG(EFF(-1))) remains significant (p = 0.0376), the current differenced values of energy efficiency and equity (ΔLOG(EFF), ΔLOG(EQQ)) are not significant, indicating that their short-run effects may depend on lag structure.

Policy Implications (Short Run):

The findings suggest that short-run policies promoting renewable energy and energy efficiency can significantly reduce emissions. However, increasing energy access (equity) must be aligned with clean energy sources to avoid raising emissions. Economic growth should be managed alongside environmental considerations to ensure a low-emission development path.

4.4.2 Long-Run Relationship (Levels Equation)

The Error Correction Model (ECM) coefficient is -0.9174 with a p-value of 0.0045, confirming a strong and statistically significant long-run relationship among the variables. This implies that approximately 91.7% of any deviation from the long-run equilibrium is corrected within one year, indicating a rapid adjustment toward stability aftershocks.

The levels equation, which captures the long-run equilibrium, highlights the sustained effects of renewable energy, energy efficiency, and GDP growth on emissions over time, reinforcing the importance of long-term energy and environmental policy coherence.

Table 7: Estimated Long Run Results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LOG(RES)	-0.432886	0.221623	-1.953257	0.0767
LOG(EFF)	-0.364704	0.122516	-2.976786	0.0126
LOG(EQQ)	1.160225	0.305395	3.799093	0.0029
GDPR	-2.287887	0.698428	-3.275767	0.0074
C	7.704765	0.980053	7.861576	0.0000

Source: Authors' Computation (2025) using E-views 10

Table 7 presents the long-run coefficients of the ARDL model:
Renewable energy share (LOG(RES)) has a negative coefficient of -0.4329, indicating that increasing the share of renewable energy in electricity generation leads to long-term reductions in emissions. Energy efficiency (LOG(EFF)) also shows a negative long-term effect (-0.3647), reinforcing the importance of sustained efficiency improvements for lowering emissions over time. Energy equity (LOG(EQQ)) has a positive coefficient of 1.1602, suggesting that while greater access to energy may benefit the population, it can lead to higher emissions in the long run—likely due to increased industrial and residential energy use. GDP growth rate (GDPR) exhibits a significant negative long-run relationship with emissions (-2.2879), supporting the idea that economic growth, when accompanied by technological progress and cleaner energy use, contributes to long-term emission reductions.

4.4.3 Model Fit and Diagnostics

Table 6 shows that, R-squared = 0.9605: The model explains 96.05% of the variation in emissions (LOG(MMT)), indicating a strong fit. Adjusted R-squared = 0.8959: Even after accounting for model complexity, the fit remains high, suggesting the model is not over-fitted. Lastly, Durbin-Watson statistic = 1.949: This value is close to 2.0, indicating that there is no significant first-order autocorrelation in the residuals—an ideal condition for model validity.

4.5 Post Estimation Diagnostic Tests

Table 8: Breusch-Godfrey Serial Correlation LM Test and **Heteroscedasticity Test**

	F-statistic	**Probability value**
Breusch-Godfrey Serial Correlation LM Test	3.499177	0.0695
Heteroskedasticity Test: Breusch-Pagan-Godfrey	0.362764	0.9727

Source: Authors' Computation (2025) using E-views 10

4.5.1 Breusch-Godfrey Serial Correlation LM Test:

This test checks for serial correlation in the residuals of the regression model. As shown in Table 8, the p-value is greater than 0.05, indicating that the study fails to reject the null hypothesis of no serial correlation. There is no evidence of autocorrelation in the residuals up to lag 3, which supports the validity of the model's standard errors, t-statistics, and confidence intervals.

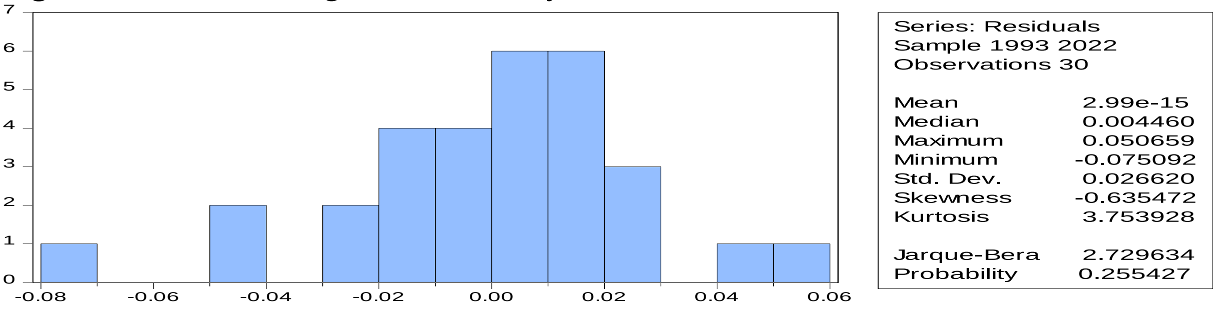
4.5.2 Heteroscedasticity Test (Breusch-Pagan-Godfrey):

This test assesses whether the residuals have constant variance (homoscedasticity). A p-value above 0.05 and an F-statistic of 0.362764 (as shown in Table 8) indicate that the study fails to reject the null hypothesis of homoscedasticity. This means there is no strong evidence of heteroscedasticity, and the model's standard errors and inferences remain reliable.

4.5.3 Normality Test

The histogram of residuals looks roughly bell-shaped**,** suggesting an approximately normal distribution as shown in figure 1 below:

Figure 1: Residual Histogram & Normality Test



In figure 1, Jarque-Bera = 2.7296, p-value > 0.05. Residuals are normally distributed low skewness, and acceptable kurtosis.

4.5.4 CUSUM (Cumulative Sum) Stability Test

CUSUM (Cumulative Sum) Stability Test is commonly used to check the parameter stability of a regression model over time.

Figure 2: CUSUM (Cumulative Sum)

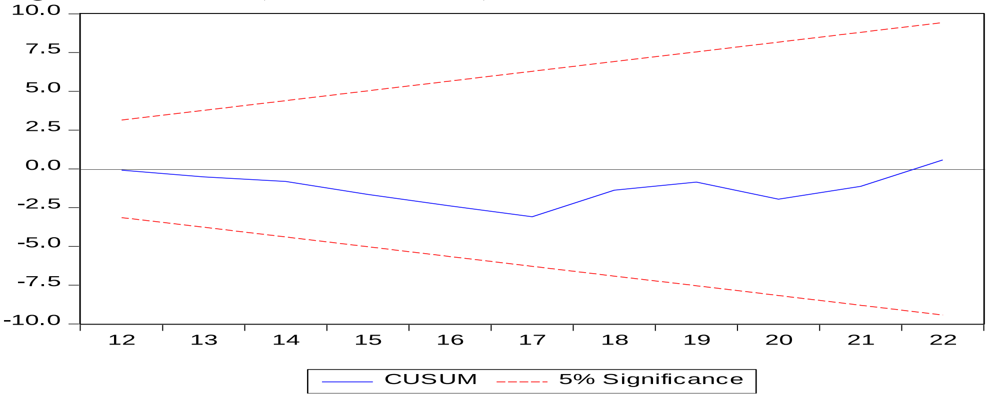
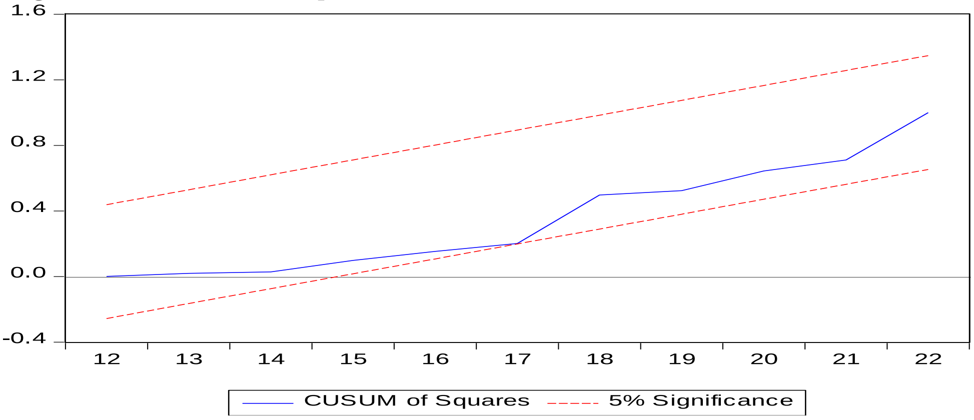


Figure 2 is a CUSUM (Cumulative Sum) Stability Test result. The CUSUM line (blue) stays within the red 5% significance bounds throughout the entire period. This indicates that the regression coefficients are stable over time at the 5% significance level. No structural breaks or parameter instability are detected. This supports the reliability of the model for forecasting or policy analysis, assuming no new structural shocks occur.

4.5.5 CUSUM of Squares Stability test

CUSUM of Squares test graph is a companion to the standard CUSUM test and it helps to assess the stability of the variance of the regression residuals over time. This is presented in figure 3 below:

Figure 3: CUSUM of Squares test



In figure 3, the CUSUM of Squares line (blue) stays within the red 5% significance bounds. This indicates no significant structural instability in the variance of the model's residuals. The variability (variance) of the residuals is stable across the time period. Thus, the model passes the CUSUM of Squares test, suggesting variance stability, an important assumption for valid inference and forecasting.

Discussion on Findings

The ARDL model results covering both short-run dynamics and long-run relationships provide crucial insights into how renewable energy, energy efficiency, energy equity, and GDP growth affect environmental pollution (emissions) in Nigeria. Renewable energy (RES) consistently shows a negative relationship with emissions in both the short and long run, supporting studies by Eze & Chinemeogo (2024) and Elum & Momodu (2017). However, the marginal significance of the long-run coefficient (p = 0.0767) may reflect implementation delays or infrastructure limitations, as highlighted by Ugwu et al. (2022) and Adeyanju et al. (2020)**.** Energy efficiency (EFF) also has a significant negative effect on emissions across both time horizons. This aligns with Eluwa et al. (2022) and Sovacool et al. (2020**)**, emphasizing the role of green technologies and demand-side management in emission reduction.

Furthermore, Energy equity (EQQ) shows a positive and significant relationship with emissions, indicating that while increasing energy access is socially beneficial, it can raise pollution levels when powered by non-renewable sources. This supports the findings of Aliyu et al. (2018) and Akinyele et al. (2015) and echoes Sobajo (2024), who argues for integrating energy equity with renewable solutions to prevent rebound effects. GDP growth (GDPR) shows a negative and significant association with emissions in both the short and long run, confirming the Environmental Kuznets Curve (EKC) hypothesis. This finding is consistent with Akinpelumi et al. (2024)**,** Nyiwul (2017**)**, and Nwozor et al. (2021**)**, who argue that economic growth paired with institutional quality, can lead to environmental improvements.

4.7 Policy Implications

The study offers Nigeria-specific policy implications grounded in the empirical results:

Renewable energy adoption presents a critical opportunity for Nigeria to reduce emissions and foster inclusive growth. However, this requires more than technical solutions—it must integrate industrial policy and circular economy principles. Policies should mainstream renewable energy into financial, industrial, and environmental systems to realize long-term sustainability and resilience.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The study used the ARDL model to assess how renewable energy, energy efficiency, energy equity, and economic growth affect environmental pollution in Nigeria. It found that renewable energy and efficiency help reduce emissions in both the short and long run, while economic growth supports the EKC hypothesis by eventually lowering pollution. However, broader energy access without cleaner sources increases emissions. The results highlight the need for a balanced policy approach that fosters economic development and environmental sustainability while ensuring equitable access to clean energy.

5.2 Policy Recommendations

Based on the empirical evidence and the broader literature, the following policy recommendations are proposed:

The government should strengthen policies that support renewable energy deployment such as solar, wind, and biomass—especially in rural and urban areas. This will reduce dependence on fossil fuels and lower emissions while improving energy access.

Implementation of national energy efficiency programs—such as retrofitting old infrastructure, promoting energy-saving appliances, and supporting smart grid technologies—should be prioritized. Regulatory bodies must enforce standards that reduce energy waste across sectors.

While expanding access to energy is vital, it should be done through low-carbon and renewable sources. Subsidies and incentives should be redirected from fossil fuels to clean energy technologies that serve marginalized and off-grid communities.

Policymakers should foster green growth strategies that promote industrialization without compromising environmental integrity. Investments in green infrastructure, eco-friendly manufacturing, and digital technologies can support a low-emission growth path.

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