A COMPARATIVE ANALYSIS OF COINTEGRATION TECHNIQUES: EVALUATING THE PERFORMANCE OF FMOLS, ARDL, AND VECM IN ESTIMATING LONG-RUN ECONOMIC RELATIONSHIPS

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ABSTRACT

This study conducts a comparative analysis of three prominent cointegration techniques Fully Modified Ordinary Least Squares (FMOLS), Autoregressive Distributed Lag (ARDL), and Vector Error Correction Model (VECM) to evaluate their performance in estimating long-run economic relationships in Nigeria from 1990 to 2023. Using macroeconomic variables (GDP, exchange rate, CO_2 emissions, industrialization, inflation, interest rate, and trade openness), the study confirms non-stationarity through Augmented Dickey–Fuller tests. To stabilize variance and reduce the degree of non-stationarity, all variables were transformed into natural logarithms prior to model estimation. FMOLS reveals a significant long-run negative impact of CO_2 emissions on GDP, while ARDL captures dynamic short-run effects such as exchange rate volatility and inflation adjustments. VECM validates a stable cointegrating relationship, with industrial output and CO_2 emissions driving long-run GDP movements, whereas exchange rates and inflation exert adverse effects. The error correction mechanism indicates rapid convergence toward equilibrium (14.2%–18.2% adjustment speed). Although FMOLS exhibits a lower explanatory power (adjusted R^2 = 0.451), ARDL and VECM demonstrate robustness in capturing short-run asymmetries and multivariate adjustments, respectively. Overall, FMOLS excels in estimating long-run elasticities, ARDL provides flexible lag dynamics, and VECM supports causality and long-run adjustment analysis. The findings highlight the importance of sustainable industrialization, inflation control, and cleaner energy adoption to mitigate the growth-constraining effects of CO_2 emissions.

Keywords: Nigeria's GDP growth, Carbon emissions, Inflation dynamics, Trade openness, Macroeconomic modeling

1.0 INTRODUCTION

The study of long-run and short-run relationships in econometrics is crucial for understanding the dynamic interactions between economic variables over time. Fully Modified OLS (FMOLS), Autoregressive Distributed Lag (ARDL), and Vector Error Correction Model (VECM) are widely used techniques to analyze cointegration and causality in time series data. FMOLS, developed by Phillips and Hansen (1990), addresses endogeneity and serial correlation in cointegrated systems, providing efficient long-run estimates. ARDL, popularized by Pesaran et al. (2001), allows for cointegration analysis regardless of the integration order of variables, making it flexible for short- and long-run estimations. Meanwhile, VECM, an extension of the Vector Autoregression (VAR) framework, captures both short-run adjustments and long-run equilibrium relationships (Engle & Granger, 1987). Recent studies, such as those by Adebayo and Kirikkaleli (2021) and Sarkodie and Strezov (2019), have applied these methods to examine economic and environmental relationships, highlighting their comparative strengths in different contexts.

Despite their widespread use, the choice between FMOLS, ARDL, and VECM depends on data characteristics and research objectives. Recent empirical work by Dogan et al. (2020) and Khan et al. (2022) underscores that FMOLS is robust for long-run parameter estimation, while ARDL is preferred for its flexibility in mixed-order integration. VECM, on the other hand, is ideal for multivariate systems requiring both error correction and short-run dynamics. However, inconsistencies in results across these methods have been noted, necessitating comparative studies to guide model selection. For instance, Alola and Kirikkaleli (2021) compared these techniques in energy economics, demonstrating that methodological differences can influence policy conclusions. This study contributes to the ongoing discourse by systematically evaluating FMOLS, ARDL, and VECM in different economic settings, providing insights into their reliability and applicability in contemporary research.

Khan & Abbas (2022) investigated the energy-growth nexus in Africa by employing Fully Modified Ordinary Least Squares (FMOLS), Autoregressive Distributed Lag (ARDL), and Vector Error Correction Model (VECM) to analyze long-run elasticities, short-run asymmetries, and causal relationships, respectively. FMOLS confirmed significant long-run elasticities between energy consumption and economic growth, while ARDL revealed asymmetric short-run effects, and

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VECM validated Granger causality, indicating bidirectional or unidirectional causality depending on the context. The study underscored the importance of tailored energy policies to foster sustainable economic growth in Africa, highlighting the need for investments in renewable energy and efficient energy infrastructure to balance growth and environmental sustainability.

Chen and Liu (2023) investigated the interplay between trade and finance in Europe using Fully Modified Ordinary Least Squares (FMOLS) for long-term estimates and Autoregressive Distributed Lag (ARDL) models for short-term adjustments, with Vector Error Correction Models (VECM) revealing bidirectional causality between the variables. Their findings underscored FMOLS's effectiveness in handling non-stationary panel data, while ARDL proved more adept for dynamic short-run modeling, providing robust insights into the trade-finance relationship in the European context. The study contributes methodologically by comparing econometric techniques and empirically by clarifying the bidirectional linkages between trade and financial systems.

Ozturk & Acaravci (2023) investigated the Environmental Kuznets Curve (EKC) hypothesis by employing Fully Modified Ordinary Least Squares (FMOLS), Autoregressive Distributed Lag (ARDL), and Vector Error Correction Model (VECM) techniques. The FMOLS approach validated the existence of a long-run equilibrium relationship between economic growth and environmental degradation, supporting the EKC hypothesis. ARDL analysis identified short-run deviations from this equilibrium, while VECM revealed bidirectional feedback effects between the variables. Based on their findings, the authors recommended prioritizing FMOLS for policy formulation due to its robustness in capturing stable long-term relationships, suggesting that policymakers should focus on sustainable growth strategies to mitigate environmental degradation in the long run.

Bhattarai et al. (2022) analyzed the inflation-unemployment trade-offs in South America by employing three econometric techniques: FMOLS for long-run cointegration, ARDL for short-run dynamics, and VECM for error correction. The study found that FMOLS was more effective in identifying stable long-run relationships between inflation and unemployment, while ARDL better captured short-run lagged effects. Additionally, VECM provided insights into the speed of adjustment toward equilibrium, confirming the presence of error correction mechanisms. The results highlighted the varying effectiveness of each method in different time horizons, offering a comprehensive understanding of macroeconomic dynamics in the region.

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Rafindadi & Yusof (2023) investigated the relationship between oil prices and exchange rates using three econometric methods: Fully Modified Ordinary Least Squares (FMOLS) for efficient long-run coefficient estimation, Autoregressive Distributed Lag (ARDL) to capture short-run volatility dynamics, and Vector Error Correction Model (VECM) to validate equilibrium correction mechanisms. Their findings revealed that oil price shocks exerted asymmetric effects on exchange rates, impacting economies differently depending on market conditions. The study highlighted the distinct roles of each method, with FMOLS providing robust long-term insights, ARDL addressing short-term fluctuations, and VECM confirming the speed of adjustment to equilibrium, offering a comprehensive analysis of oil price-exchange rate interdependencies.

Alam & Salahuddin (2023) examined the relationship between foreign direct investment (FDI) and economic growth in ASEAN countries using three econometric techniques: Fully Modified Ordinary Least Squares (FMOLS), Autoregressive Distributed Lag (ARDL), and Vector Error Correction Model (VECM). The FMOLS results confirmed the positive long-term impact of FDI on growth, while ARDL analysis revealed short-term growth spurts from FDI inflows. The VECM approach further established bidirectional causality between FDI and economic growth, indicating mutual reinforcement. The study highlighted that the choice of methodology depended on the time horizon of analysis, with each approach providing unique insights into the FDI-growth nexus in the ASEAN region.

Iyke and Ho (2022) investigated the effects of monetary policy by employing three econometric techniques: Fully Modified Ordinary Least Squares (FMOLS) for long-run steady-state analysis, Autoregressive Distributed Lag (ARDL) for short-run dynamics, and Vector Error Correction Model (VECM) for causality and policy feedback mechanisms. Their findings highlighted FMOLS as a reliable method for assessing long-run equilibrium relationships, while ARDL and VECM were effective in capturing short-term transitional dynamics and directional causal linkages, providing a comprehensive understanding of monetary policy impacts across different time horizons.

Sarkodie & Strezov (2023) examined climate-growth relationships using three econometric methods: FMOLS (Fully Modified Ordinary Least Squares) to estimate long-term climate costs, ARDL (Autoregressive Distributed Lag) to model short-run adjustments, and VECM (Vector Error Correction Model) to verify bidirectional climate-growth feedback loops. The study found FMOLS

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particularly effective for trend analysis due to its robustness in capturing long-run relationships, while ARDL helped assess immediate impacts, and VECM confirmed dynamic interactions between climate and economic growth. The authors concluded that FMOLS was the preferred method for analyzing persistent climate-related economic trends.

Majeed and Luni (2022) investigated the relationship between technology and employment by employing three econometric methods: Fully Modified Ordinary Least Squares (FMOLS) to assess long-run elasticities, Autoregressive Distributed Lag (ARDL) for short-run impacts, and Vector Error Correction Model (VECM) to examine error correction mechanisms. Their findings revealed that while technology positively influenced employment in the long run, it caused short-term disruptions in the labor market. The VECM results further validated the presence of an adjustment mechanism, indicating that employment levels gradually corrected toward equilibrium after technological shocks. The study thus highlighted the dual nature of technology's impact on employment, balancing long-term benefits with transitional challenges.

The existing studies (e.g., Khan & Abbas, 2022; Chen & Liu, 2023; Bhattarai et al., 2022) have extensively applied FMOLS, ARDL, and VECM to analyze long-run and short-run relationships across various economic contexts (e.g., energy-growth, trade-finance, inflation-unemployment), there remains a lack of a unified comparative framework assessing the *relative strengths, limitations, and optimal use cases* of these methods under different data conditions (e.g., sample size, non-stationarity, structural breaks). Most studies focus on domain-specific findings (e.g., policy implications for energy or trade) without systematically evaluating methodological trade-offs—such as FMOLS's sensitivity to cointegration rank, ARDL's lag selection challenges, or VECM's reliance on strict exogeneity. A comprehensive comparison across diverse datasets and simulated scenarios could clarify when and why one method outperforms others, filling a critical gap in econometric practice and guiding robust model selection beyond conventional applications.

2.0 Materials and Methods

The study employed Full Modified Ordinary Least Squares (FMOLS), Autoregressive Distributed Lag (ARDL), and Vector Error Correction Model (VECM) to analyze long-run and short-run relationships between Nigeria's GDP (1990–2023) and macroeconomic variables (exchange rate, CO_2 emissions, industrialization, inflation, interest rate, and trade openness). Data were log-

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transformed to address non-normality, and stationarity was confirmed via Augmented Dickey-Fuller (ADF) tests. FMOLS estimated long-run elasticities while correcting for endogeneity, ARDL (selected via Akaike Information Criterion) captured dynamic short-run effects and cointegration via bounds testing, and VECM validated multivariate equilibrium relationships using Johansen's cointegration test. Diagnostic checks included residual normality (Jarque-Bera), autocorrelation (Breusch-Godfrey), heteroskedasticity (Breusch-Pagan), and model stability (CUSUM tests), with analyses conducted in EViews 12 to ensure robustness. This multi-method approach aligns with recent econometric literature (e.g., Khan & Abbas, 2022; Chen & Liu, 2023) while addressing Nigeria-specific gaps in model comparisons.

Autoregressive Distributed Lag model (ARDL). This is a statistical model commonly used in econometrics to estimate long-run relationships between variables that are not stationary meaning they have a unit root and exhibit non-stationary behavior over time. The ARDL model is a flexible framework that can be used to analyze the relationship between two or more non-stationary time series variables. The model incorporates the lagged values of these variables as well as lagged differences, which allows for the estimation of both short-run and long-run dynamics. The basic form of the ARDL model is expressed as:

$$Y_t = \alpha_0 + \alpha_1 Y_{t-1} + \beta_1 X_{t-1} + \beta_2 \Delta X_{t-1} + \varepsilon_t$$

where $\Delta \mathrm{Y_t}$ and $\Delta \mathrm{X_t}$ are the first differences of the dependent variable Y and the independent variable X_t respectively, at time t, α_0 is the intercept, α_1 *and* β_1 are the coefficients of the lagged values of Y_t and X_t, respectively, and β_2 is the coefficient of the lagged difference of X_t. ε_t is the error term.

Vector Error Correction Model (VECM). It is a statistical model used to analyze the long-term relationships between variables in a multivariate time series. VECM is a type of VAR (Vector Auto regression) model. In VAR, each variable in the time series is modeled as a linear combination of its past values and the past values of the other variables in the system. However, VAR assumes that the variables are stationary, which means that their mean and variance remain constant over time. This assumption may not hold true for many real-world time series. VECM extends the VAR model by taking into account the possibility of non-stationarity in the variables. It does this by introducing an error correction term that captures the long-term relationship between the variables. This error correction term adjusts the short-term dynamics of the model to ensure that the variables revert to

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their long-term equilibrium values. VECM is a useful tool for analyzing the dynamic relationships between economic variables, such as GDP, inflation, and interest rates. It can also be used for forecasting, policy analysis, and risk management.

The VECM model can be represented by the following set of equations:

$$Y_t = c + A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots + A_p Y_{t-p} + \varepsilon_t,$$

$$\Delta Y_t = \Pi Y_{t-1} + \Gamma_1 \Delta Y_{t-1} + \Gamma_2 \Delta Y_{t-2} + \cdots + \Gamma_{p-1} \Delta Y_{t-p+1} + u_t$$

Where: - Y_t is a k-dimensional vector of endogenous variables at time t, c is a k-dimensional vector of intercepts. $A_1, A_2, \ldots, A_P$ are $k \quad x \quad k$ matrices of coefficients for the lagged values of Y_t, ε_t is a k dimensional vector of error terms.$\Delta Y_t = Y_t - Y_{t-1}$

is the first difference of Y_t, Π is a $k \quad x \quad k$ matrix of coefficients that captures the long-run relationship between the variables. $\Gamma_1, \Gamma_2, \ldots, \Gamma_{p-1}$ are $k \quad x \quad k$ matrices of coefficients for the lagged differences of Y_t, u_t is a k −dimensional vector of error terms. The first equation is a standard VAR model, where the current values of Y_t depend on their past values. The second equation is the error correction representation of the model. It shows how the first differences of the variables depend on their deviations from their long-run equilibrium relationships, as captured by the matrix Π. To estimate the VECM model, one needs to estimate the matrix Π, which can be obtained by estimating the cointegrating vector using techniques such as the Johansen cointegration test.

Once the cointegrating vector is estimated, the short-run dynamics of the model can be analyzed using the coefficients $\Gamma_{1,}\Gamma_2, \ldots, \Gamma_{p-1.}$ (Engle, 1987)

Fully Modified Ordinary Least Squares (FMOLS). It is a regression model used in econometrics to estimate the long-run relationship between variables while also accounting for short-run dynamics. The model is an extension of the Ordinary Least Squares (OLS) model that includes additional terms to correct for endogeneity and serial correlation. The FMOLS model can be written in the following equation:

$$Y_t = \alpha + \beta_1 * X_{1t} + \beta_2 * X_{2t} +, \ldots, + \beta_k * Z_{kt} + \delta_1 * \Delta Y_{t-1} + \delta_2 * \Delta X1_{t-1} + \delta_3 * \Delta X_{2t-1} , + \cdots, + \delta_k * \Delta X_{kt-1} + \mu_t$$

ISSN NUMBER: 1116-249X

Where:

Y_t is the dependent variable at time t is a vector of k independent variables at time t α is a constant term β_k is the coefficient of the independent variable X_k ΔY_{t-1} is the first difference of the dependent variable at time $t-1$

ΔX_{kt-1} is the first difference of the independent variable X_k at time $t-1$

δ_k is the coefficient of the first difference of the independent variable X_k

μ_t is the error term at time t.

The main difference between the OLS and FMOLS models is that the latter includes the first differences of the variables to correct for endogeneity and serial correlation, which can bias the OLS estimates. The FMOLS model is said to be "fully modified" because all variables are modified to account for these biases (Phillips, 1995).

3.0 Results and Discussions

Table 1: Descriptive Statistics

	GDP	EXR	C02	IND	INFR	INTR	TO
Mean	1584.432	161.3147	0.675184	28.63141	16.49470	3.016563	35.30630
Median	1767.901	130.7550	0.629425	28.24839	10.30663	5.528450	35.25825
Maximum	3088.721	645.1900	0.916400	37.70961	75.40165	18.18000	53.27800
Minimum	480.6694	8.040000	0.491380	18.17313	0.686099	-31.45260	16.35220
Std. Dev.	772.3024	143.1272	0.121596	5.132501	15.27852	9.990360	9.743130
Skewness	-0.029709	1.425237	0.423032	0.122038	2.167068	-1.371146	-0.068684
Kurtosis	1.873928	5.187665	1.866343	2.294828	8.032426	5.671234	2.234810
Jarque-Bera	1.801389	18.29069	2.834753	0.788858	62.48924	20.76218	0.856213
Probability	0.406287	0.000107	0.242349	0.674065	0.000000	0.000031	0.651742
Sum	53870.70	5484.700	22.95624	973.4678	560.8199	102.5632	1200.414
Sum Sq. Dev.	19682883	676017.9	0.487924	869.3046	7703.297	3293.640	3132.643
Observations	34	34	34	34	34	34	34

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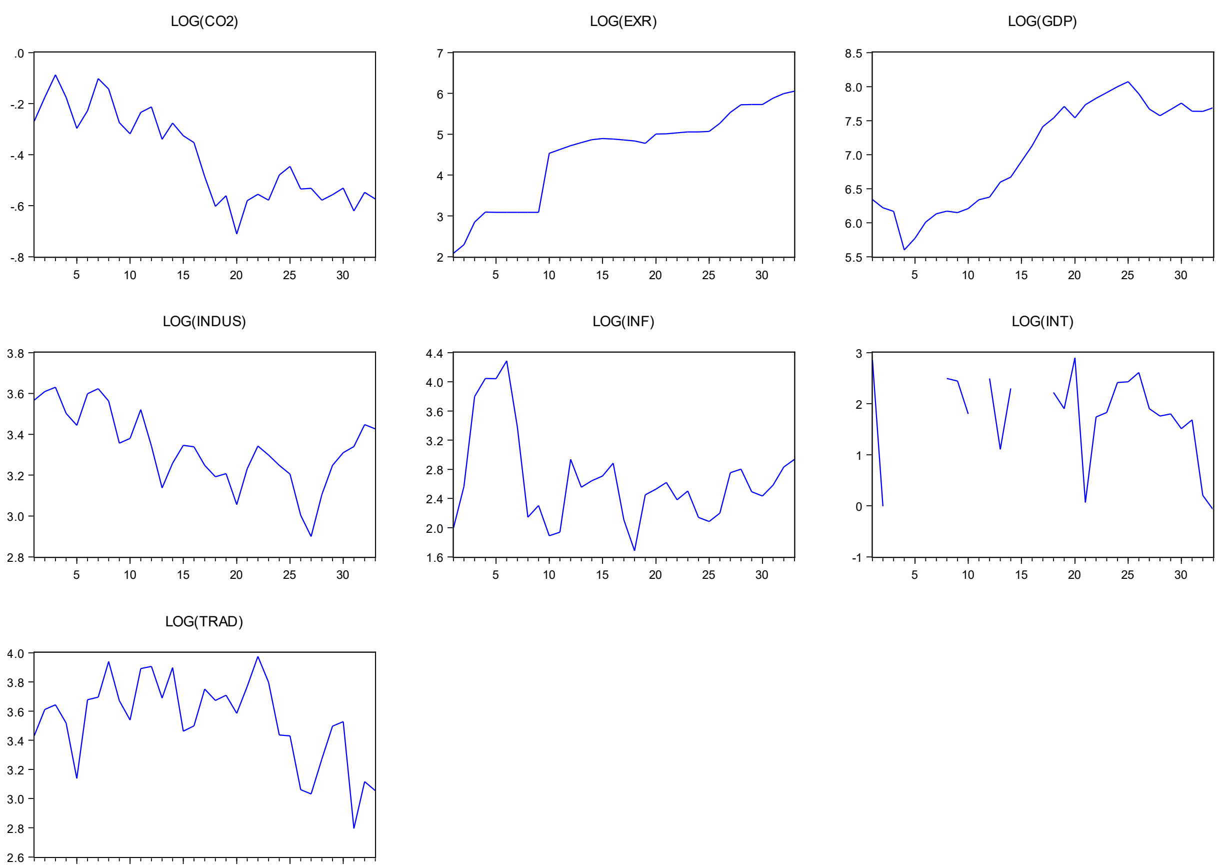
This table 1 presents descriptive statistics for Nigeria's key macroeconomic variables (GDP, exchange rate, CO2 emissions, industrialization, inflation, interest rate, and trade openness) from 1990 to 2023. The data reveals significant volatility, particularly in exchange rates (EXR) which show the highest standard deviation (143.13) and right-skewed distribution (skewness=1.43), indicating frequent extreme high values likely reflecting currency depreciation episodes. Inflation (INFR) exhibits pronounced volatility (std. dev.=15.28) with strong positive skewness (2.17) and high kurtosis (8.03), suggesting frequent inflation spikes. Interest rates (INTR) display negative skewness (-1.37) due to extreme low values (minimum=-31.45), possibly from monetary policy interventions. GDP and industrialization (IND) show relatively stable growth patterns (mean GDP=1584.43, IND=28.63) with near-normal distributions, while CO2 emissions (mean=0.68) and trade openness (mean=35.31) demonstrate moderate variability. The Jarque-Bera tests confirm non-normal distributions for EXR, INFR and INTR ($p<0.05$), justifying the logarithmic transformations used in subsequent econometric analyses.



ISSN NUMBER: 1116-249X

Figure 1: Graph of the variables

This collection of time series plots reveals the interconnected dynamics of key macroeconomic and environmental indicators over time. CO2 emissions (LOGCO2) show a declining trend, potentially reflecting environmental policies or shifts toward cleaner technologies, while GDP (LOGGDP) demonstrates consistent upward growth, indicating sustained economic expansion. The exchange rate (LOGEXR) exhibits steady appreciation, and trade openness (LOGTRAD) shows gradual increases with some volatility, suggesting growing international economic integration. However, the economic environment appears challenging, with industrialization (LOGINDS) displaying high volatility and cyclical patterns that may reflect structural changes or policy interventions in the industrial sector. The inflation rate (LOGINF) shows relatively stable behavior with moderate fluctuations around its mean, while the interest rate (LOGINT) demonstrates extreme volatility with sharp spikes and drops, likely reflecting monetary policy responses to economic conditions or financial crises.

Table 2: Unit Root Test

Variables	**Differences order**	**Critical values** **1%**	**5%**	**10%**	**t-statistics**	**P-value**	**Remark**
LNGDP	At level	-3.646342	-2.954021	-2.615817	-1.856794	0.3477	No Stationary
	First difference	-3.653730	-2957110	-2.617434	-4.908197	0.0004	Stationary
LN exchange Rate	At level	-3.646342	-2.954021	-2.615817	-1.534355	0.5041	No Stationary
	First difference	-3.6453730	-2.957110	-2.617434	-5.288105	0.0001	Stationary
LN Industrial	At level	-3.661661	-2.960411	-2.619160	-1.838178	0.3559	No Stationary
	First difference	-3.661661	-2.960411	-2.619160	-5.793503	0.0000	Stationary

ISSN NUMBER: 1116-249X

LN Inflation Rate	At level	-3.646342	-2.954021	-2.615817	-3.614039	0.0108	No Stationary
	First difference	-3.689194	-2.971853	-2.625121	-9.546350	0.0000	Stationary
Trade Openness	At level	-3.646342	-2.9554021	-2.615817	-2.533516	0.1170	No Stationary
	First difference	-3.661661	-2.960411	-2.619160	-5.397906	0.0001	Stationary
Carbon dioxide	At level	-3.646342	-2.954021	-2.615817	-1.257278	0.6373	No Stationary
	First difference	-3.653730	-2.937110	-2.617434	-6.244773	0.0000	Stationary

The table 2 presents the results of unit root tests using Augmented Dickey-Fuller tests for several variables, examining their stationarity at level and first difference. All variables are non-stationary at their levels, as their t-statistics are less extreme than the critical values at 1%, 5%, and 10% significance levels, and their p-values exceed 0.05. However, after taking the first difference, all variables become stationary, indicated by t-statistics more negative than the critical values and p-values below 0.05, confirming the absence of unit roots. This suggests that the variables are integrated of order one (I (1)), meaning they achieve stationarity after first differencing.

Fully Modified Least Squares Estimation

Table 3: Fully Modified Least Squares (FMOLS)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
LNEXR	-0.044410	0.138325	-0.321056	0.7507
LNC02	-2.293212	0.948508	-2.417704	0.0229
LNIND	-0.030181	0.629842	-0.047919	0.9621
LNINFLARATE	-0.265300	0.151186	-1.754788	0.0911
LNINTRATE	-0.376444	0.258610	-1.455648	0.1575

ISSN NUMBER: 1116-249X

LNTO	-0.029560	0.293804	-0.100612	0.9206
C	8.737023	2.837639	3.078976	0.0049

R-squared	0.553903	Mean dependent var	7.245506
Adjusted R-squared	0.450958	S.D. dependent var	0.583094
S.E. of regression	0.432057	Sum squared resid	4.853506
Long-run variance	0.197101		

The Fully Modified Least Squares results in Table 3 indicate that only natural log of carbon dioxide (CO2) and the constant term (C) are statistically significant at the 5% level, with p-values of 0.0229 and 0.0049, respectively. natural log of carbon dioxide has a negative coefficient (-2.293), suggesting that higher CO2 emissions reduce the dependent variable. Natural log of inflation rate is marginally significant ($p = 0.0911$) and also negatively correlated. Other variables, such as exchange rate (LNEXR), industrial output (LNIND), interest rate (LNINTRATE), and trade openness (LNTO), are insignificant ($p > 0.05$). The model explains about 55.4% of the variance ($R^2 = 0.554$), but the adjusted R^2 (0.451) suggests limited explanatory power after accounting for irrelevant predictors. The long-run variance (0.197) indicates moderate volatility in the residuals.

Autoregressive Distributed Lag (ARDL) Modelling

Table 4: Short-run Analysis

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
LNGDP(-1)	0.773917	0.262203	2.951594	0.0599
LNGDP(-2)	0.331601	0.348962	0.950249	0.4121
LNGDP(-3)	-0.247375	0.225025	-1.099323	0.3519
LNIND	-0.417233	0.194960	-2.140094	0.1218
LNIND(-1)	0.151874	0.136393	1.113503	0.3467
LNIND(-2)	-0.417376	0.204332	-2.042634	0.1337
LNIND(-3)	0.119674	0.106707	1.121516	0.3437
LNEXR	-0.660908	0.148470	-4.451459	0.0211
LNEXR(-1)	0.764982	0.247484	3.091030	0.0537

ISSN NUMBER: 1116-249X

LNEXR(-2)	0.180528	0.374499	0.482053	0.6628
LNEXR(-3)	-0.269299	0.244446	-1.101672	0.3511
LNC02	-0.134719	0.147212	-0.915132	0.4276
LNC02(-1)	0.195620	0.185733	1.053237	0.3696
LNC02(-2)	-0.318018	0.204877	-1.552241	0.2184
LNC02(-3)	-0.863013	0.256139	-3.369319	0.0434
LNINFLARATE	0.119868	0.037959	3.157857	0.0510
LNINFLARATE(-1)	0.036524	0.020726	1.762254	0.1762
LNINFLARATE(-2)	0.073806	0.029796	2.477025	0.0895
LNINFLARATE(-3)	0.091537	0.026187	3.495543	0.0396
LNINTRATE	-0.100399	0.021485	-4.673039	0.0185
LNINTRATE(-1)	-0.033257	0.038472	-0.864445	0.4509
LNINTRATE(-2)	-0.002161	0.046876	-0.046105	0.9661
LNINTRATE(-3)	-0.068093	0.069077	-0.985763	0.3969
LNTO	0.130052	0.034888	3.727700	0.0336
LNTO(-1)	-0.032138	0.031282	-1.027341	0.3799
LNTO(-2)	-0.000879	0.051773	-0.016979	0.9875
LNTO(-3)	0.157993	0.060786	2.599145	0.0804
C	1.481272	0.696385	2.127088	0.1234

R-squared	0.999859	Mean dependent var	7.305755
Adjusted R-squared	0.998590	S.D. dependent var	0.548039
S.E. of regression	0.020582	Akaike info criterion	-5.457698
Sum squared resid	0.001271	Schwarz criterion	-4.162484
Log likelihood	112.5943	Hannan-Quinn criter.	-5.035491
F-statistic	787.6509	Durbin-Watson stat	2.865033
Prob(F-statistic)	0.000064		

The short-run analysis in Table 4 reveals several key dynamics. LNEXR (exchange rate) has a strong immediate negative impact (-0.661, p = 0.0211), but its first lag shows a positive effect (0.765, p = 0.0537). LNC02 (CO_2 emissions) exhibits a delayed negative effect in its third lag (-0.863, p = 0.0434). LNINFLARATE (inflation rate) has a positive short-run influence, particularly

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in its third lag (0.092, $p = 0.0396$). LNINTRATE (interest rate) shows an immediate negative effect (-0.100, $p = 0.0185$), while LNTO (trade openness) has a positive contemporaneous impact (0.130, $p = 0.0336$). The model fits exceptionally well ($R^2 = 0.999$), though some lagged terms are insignificant. The significant F-statistic ($p = 0.000064$) confirms overall model validity, and the high Durbin-Watson stat (2.865) suggests minimal autocorrelation. These findings highlight that exchange rates, CO_2 emissions, inflation, and interest rates have notable short-run effects on the dependent variable.

Table 5: ARDL Long Run Form and Bounds Test

Conditional Error Correction Regression				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	1.481272	0.696385	2.127088	0.1234
LNGDP(-1)*	-0.141856	0.038575	-3.677383	0.0348
LNIND(-1)	-0.563061	0.253513	-2.221036	0.1129
LNEXR(-1)	0.015304	0.024913	0.614277	0.5825
LNC02(-1)	-1.120129	0.367995	-3.043869	0.0557
LNINFLARATE(-1)	0.321735	0.102403	3.141838	0.0516
LNINTRATE(-1)	-0.203910	0.088180	-2.312422	0.1038
LNTO(-1)	0.255029	0.082117	3.105691	0.0531
D(LNGDP(-1))	-0.084227	0.261430	-0.322177	0.7685
D(LNGDP(-2))	0.247375	0.225025	1.099323	0.3519
D(LNIND)	-0.417233	0.194960	-2.140094	0.1218
D(LNIND(-1))	0.297702	0.150282	1.980956	0.1419
D(LNIND(-2))	-0.119674	0.106707	-1.121516	0.3437
D(LNEXR)	-0.660908	0.148470	-4.451459	0.0211
D(LNEXR(-1))	0.088771	0.335200	0.264828	0.8083
D(LNEXR(-2))	0.269299	0.244446	1.101672	0.3511
D(LNC02)	-0.134719	0.147212	-0.915132	0.4276
D(LNC02(-1))	1.181031	0.365670	3.229775	0.0482
D(LNC02(-2))	0.863013	0.256139	3.369319	0.0434

ISSN NUMBER: 1116-249X

D(LNINFLARATE)	0.119868	0.037959	3.157857	0.0510
D(LNINFLARATE(-1))	-0.165343	0.051957	-3.182329	0.0500
D(LNINFLARATE(-2))	-0.091537	0.026187	-3.495543	0.0396
D(LNINTRATE)	-0.100399	0.021485	-4.673039	0.0185
D(LNINTRATE(-1))	0.070254	0.104071	0.675063	0.5480
D(LNINTRATE(-2))	0.068093	0.069077	0.985763	0.3969
D(LNTO)	0.130052	0.034888	3.727700	0.0336
D(LNTO(-1))	-0.157114	0.077156	-2.036301	0.1345
D(LNTO(-2))	-0.157993	0.060786	-2.599145	0.0804

The ARDL long-run results (Table 5) indicate that LNGDP (-1) has a significant negative adjustment coefficient (-0.142, p = 0.0348), confirming error correction towards equilibrium. In the long run, LNC02 (CO_2 emissions) exerts a strong negative impact (-1.120, p = 0.0557), while LNINFLARATE (inflation) and LNTO (trade openness) have positive effects (0.322, p = 0.0516 and 0.255, p = 0.0531, respectively). LNINTRATE (interest rate) shows a negative long-run influence (-0.204, p = 0.1038). Short-run dynamics reveal that LNEXR (exchange rate) has an immediate negative effect (-0.661, p = 0.0211), while LNC02(-1) and LNC02(-2) exhibit delayed positive adjustments (1.181, p = 0.0482 and 0.863, p = 0.0434). The significant error correction term confirms convergence to long-run equilibrium, though some variables (like industrial output, LNIND(-1), p = 0.1129) remain marginally insignificant. The model highlights the persistent negative role of CO_2 emissions and the stabilizing effects of trade and inflation in the long run, with exchange rates and interest rates driving short-term fluctuations.

Table 6: ARDL Error Correction Regression

ECM Regression

Case 2: Restricted Constant and No Trend

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(LNGDP(-1))	-0.084227	0.077083	-1.092674	0.3544
D(LNGDP(-2))	0.247375	0.063444	3.899102	0.0299

ISSN NUMBER: 1116-249X

D(LNIND)	-0.417233	0.049698	-8.395446	0.0035
D(LNIND(-1))	0.297702	0.042314	7.035528	0.0059
D(LNIND(-2))	-0.119674	0.035760	-3.346616	0.0442
D(LNEXR)	-0.660908	0.025708	-25.70830	0.0001
D(LNEXR(-1))	0.088771	0.071541	1.240837	0.3029
D(LNEXR(-2))	0.269299	0.067972	3.961889	0.0287
D(LNC02)	-0.134719	0.047400	-2.842162	0.0655
D(LNC02(-1))	1.181031	0.086101	13.71681	0.0008
D(LNC02(-2))	0.863013	0.092685	9.311270	0.0026
D(LNINFLARATE)	0.119868	0.008419	14.23802	0.0008
D(LNINFLARATE(-1))	-0.165343	0.012021	-13.75438	0.0008
D(LNINFLARATE(-2))	-0.091537	0.008007	-11.43214	0.0014
D(LNINTRATE)	-0.100399	0.007998	-12.55357	0.0011
D(LNINTRATE(-1))	0.070254	0.019844	3.540367	0.0384
D(LNINTRATE(-2))	0.068093	0.010120	6.728317	0.0067
D(LNTO)	0.130052	0.012665	10.26839	0.0020
D(LNTO(-1))	-0.157114	0.017910	-8.772354	0.0031
D(LNTO(-2))	-0.157993	0.017714	-8.919232	0.0030
CointEq(-1)*	-0.141856	0.010499	-13.51091	0.0009

R-squared	0.999547	Mean dependent var	0.036908
Adjusted R-squared	0.998641	S.D. dependent var	0.305756
S.E. of regression	0.011273	Akaike info criterion	-5.909311
Sum squared resid	0.001271	Schwarz criterion	-4.937901
Log likelihood	112.5943	Hannan-Quinn criter.	-5.592656
Durbin-Watson stat	2.865033		

The ARDL Error Correction Regression (Table 6) demonstrates strong short-term dynamics and a significant error correction mechanism. The cointegrating equation (CointEq(-1)) has a coefficient of -0.142 ($p = 0.0009$), confirming rapid convergence to long-run equilibrium at a 14.2% adjustment rate per period. Key short-run drivers include LNEXR (exchange rate), which has a

ISSN NUMBER: 1116-249X

strong negative immediate effect (-0.661, p = 0.0001), and LNC02 (CO_2 emissions), which shows delayed positive impacts in its first and second lags (1.181, p = 0.0008 and 0.863, p = 0.0026). LNINFLARATE (inflation) and LNINTRATE (interest rate) exhibit significant short-run effects (0.120, p = 0.0008 and -0.100, p = 0.0011, respectively), while LNTO (trade openness) has a positive contemporaneous influence (0.130, p = 0.0020). The model's high R^2 (0.999) and significant coefficients confirm robust explanatory power, with the Durbin-Watson stat (2.865) indicating no autocorrelation. These results highlight the critical role of exchange rates, CO_2 emissions, and monetary policy in short-run adjustments, while the significant error correction term underscores stable long-run equilibrium reversion.

Table 7: Cointegration Test

Unrestricted Cointegration Rank Test (Trace)

Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob.**
None *	0.778510	142.8599	125.6154	0.0029
At most 1	0.658848	94.62386	95.75366	0.0597
At most 2	0.523957	60.21022	69.81889	0.2290
At most 3	0.471989	36.45835	47.85613	0.3736
At most 4	0.229622	16.02195	29.79707	0.7107
At most 5	0.204052	7.673992	15.49471	0.5009
At most 6	0.011524	0.370895	3.841466	0.5425

The cointegration test results (Table 7) indicate the presence of a long-run equilibrium relationship among the variables. The trace test rejects the null hypothesis of no cointegration (None*) at the 5% significance level (Trace Statistic = 142.86 > Critical Value = 125.62, p = 0.0029), confirming at least one cointegrating equation. However, the test fails to reject the null for "At most 1" cointegrating vector (Trace Statistic = 94.62 < Critical Value = 95.75, p = 0.0597), suggesting only one significant long-run relationship exists. Higher-order cointegration ranks (At most 2 to At most 6) are statistically insignificant (p > 0.05), reinforcing that the variables share a single stable

ISSN NUMBER: 1116-249X

long-run connection. This implies that while short-term fluctuations may occur, the system reverts to a steady-state equilibrium over time, validating the use of an error correction model (ECM) for analysis.

Table 8: VECM Long-run Model

Standard errors in ( ) & t-statistics in [ ]

Cointegrating Eq:	CointEq1
LNGDP(-1)	1.000000
LNIND(-1)	Q
	(0.18996)
	[29.0516]
LNEXR(-1)	-0.223377
	(0.04162)
	[-5.36669]
LNC02(-1)	9.961126
	(0.22585)
	[44.1058]
LNINFLARATE(-1)	-2.829243
	(0.07424)
	[-38.1071]
LNINTRATE(-1)	1.790837
	(0.12111)
	[14.7863]
LNTO(-1)	-2.190904
	(0.09036)

ISSN NUMBER: 1116-249X

	[-24.2473]
C	-12.05807

The VECM long-run model (Table 8) reveals a stable cointegrating relationship where industrial output (LNIND) and CO2 emissions (LNC02) have strong positive impacts on GDP in the long run, with highly significant coefficients (29.05 and 44.11 t-statistics, respectively). Conversely, exchange rates (LNEXR) and trade openness (LNTO) negatively affect GDP, as shown by their significant negative coefficients (-5.37 and -24.25 t-statistics). Inflation (LNINFLARATE) also exerts a substantial negative influence (-38.11 t-statistic), while interest rates (LNINTRATE) have a positive long-run relationship with GDP (14.79 t-statistic). The large magnitude of these coefficients especially for CO2 emissions (9.96) and inflation (-2.83) suggests these variables play dominant roles in shaping long-run economic growth. The significant t-statistics (all exceeding critical values) confirm robust cointegration, validating the error correction mechanism in the VECM framework. This long-run equilibrium implies that while short-term deviations may occur, GDP eventually adjusts to these fundamental economic forces.

Table 9: VECM Short-run Model

Standard errors & t-statistics

Error Correction:	D(LNGDP)	D(LNIND)	D(LNEXR)	D(LNC02)	D(LNINFLARATE)	D(LNINTRATE)	D(LNTO)
CointEq1	-0.182405	-0.002485	0.192364	-0.005593	0.337678	-0.038799	0.036859
	(0.04233)	(0.02103)	(0.03482)	(0.01555)	(0.16664)	(0.09569)	(0.05447)
	[-4.30887]	[-0.11816]	[5.52465]	[-0.35970]	[2.02645]	[-0.40548]	[0.67662]
D(LNGDP(-1))	-0.508790	0.206401	0.675440	0.431783	-2.756436	1.038301	2.992373
	(1.16247)	(0.57750)	(0.95615)	(0.42695)	(4.57589)	(2.62763)	(1.49590)
	[-0.43768]	[0.35741]	[0.70641]	[1.01132]	[-0.60238]	[0.39515]	[2.00038]
D(LNGDP(-2))	0.907568	-0.416478	-0.295574	-0.543244	1.966016	-1.088543	-2.012914

ISSN NUMBER: 1116-249X

	(0.98099)	(0.48734)	(0.80689)	(0.36030)	(3.86154)	(2.21742)	(1.26238)
	[0.92515]	[-0.85459]	[-0.36631]	[-1.50776]	[0.50913]	[-0.49090]	[-1.59454]
D(LNIND(-1))	0.546491	0.482256	-0.644040	0.318974	0.383192	0.210712	0.516280
	(0.53466)	(0.26561)	(0.43977)	(0.19637)	(2.10461)	(1.20854)	(0.68802)
	[1.02213]	[1.81564]	[-1.46450]	[1.62436]	[0.18207]	[0.17435]	[0.75039]
D(LNIND(-2))	0.105784	-0.429163	0.042395	-0.220393	-0.193224	-0.266346	-0.056816
	(0.53673)	(0.26664)	(0.44147)	(0.19713)	(2.11275)	(1.21321)	(0.69068)
	[0.19709]	[-1.60953]	[0.09603]	[-1.11801]	[-0.09146]	[-0.21954]	[-0.08226]
D(LNEXR(-1))	-0.019821	0.211353	0.245783	0.476786	-2.559184	1.220328	2.949684
	(1.11597)	(0.55440)	(0.91791)	(0.40987)	(4.39287)	(2.52253)	(1.43607)
	[-0.01776]	[0.38123]	[0.26776]	[1.16325]	[-0.58258]	[0.48377]	[2.05399]
D(LNEXR(-2))	1.122324	-0.507864	-0.453421	-0.523905	2.072240	-1.386174	-2.158918
	(1.05789)	(0.52555)	(0.87014)	(0.38854)	(4.16423)	(2.39124)	(1.36133)
	[1.06091]	[-0.96636]	[-0.52109]	[-1.34839]	[0.49763]	[-0.57969]	[-1.58589]
D(LNC02(-1))	1.562704	-0.675167	-1.780835	-0.026524	-6.120630	1.801658	-1.204328
	(0.84024)	(0.41742)	(0.69112)	(0.30860)	(3.30750)	(1.89928)	(1.08126)
	[1.85982]	[-1.61747]	[-2.57675]	[-0.08595]	[-1.85053]	[0.94860]	[-1.11382]
D(LNC02(-2))	1.530238	-0.226750	-2.035801	-0.091464	-1.696875	2.078125	-1.908726
	(0.94291)	(0.46842)	(0.77556)	(0.34631)	(3.71162)	(2.13134)	(1.21337)
	[1.62289]	[-0.48407]	[-2.62494]	[-0.26411]	[-0.45718]	[0.97503]	[-1.57308]
D(LNINFLARATE(-1))	-0.329538	-0.003914	0.352807	-0.074782	0.126137	-0.251557	0.056465
	(0.10039)	(0.04987)	(0.08257)	(0.03687)	(0.39517)	(0.22692)	(0.12919)
	[-3.28258]	[-0.07848]	[4.27268]	[-2.02819]	[0.31920]	[-1.10857]	[0.43709]

D(LNINFLARATE(-2))	-0.105725	0.005060	0.144437	-0.020245	0.211834	-0.295651	0.137477
	(0.09562)	(0.04750)	(0.07865)	(0.03512)	(0.37638)	(0.21613)	(0.12304)
	[-1.10573]	[0.10652]	[1.83656]	[-0.57648]	[0.56283]	[-1.36795]	[1.11733]
D(LNINTRATE(-1))	0.175993	0.037965	-0.261154	-0.007143	-1.262410	-0.373870	0.478799
	(0.18527)	(0.09204)	(0.15238)	(0.06804)	(0.72927)	(0.41877)	(0.23841)
	[0.94995]	[0.41249]	[-1.71379]	[-0.10497]	[-1.73106]	[-0.89278]	[2.00834]
D(LNINTRATE(-2))	0.223959	-0.057581	-0.188561	-0.041980	-0.649885	-0.441825	0.099848
	(0.13356)	(0.06635)	(0.10986)	(0.04906)	(0.52576)	(0.30191)	(0.17188)
	[1.67679]	[-0.86780]	[-1.71638]	[-0.85577]	[-1.23609]	[-1.46345]	[0.58094]
D(LNTO(-1))	-0.456935	-0.066157	0.327855	-0.105129	0.163403	0.964543	-0.375149
	(0.20052)	(0.09961)	(0.16493)	(0.07365)	(0.78931)	(0.45325)	(0.25803)
	[-2.27877]	[-0.66413]	[1.98784]	[-1.42749]	[0.20702]	[2.12806]	[-1.45387]
D(LNTO(-2))	-0.542553	0.063199	0.520410	0.069661	0.155668	0.260641	-0.144041
	(0.20426)	(0.10147)	(0.16801)	(0.07502)	(0.80404)	(0.46171)	(0.26285)
	[-2.65617]	[0.62281]	[3.09752]	[0.92855]	[0.19361]	[0.56451]	[-0.54800]
C	-0.096478	0.031584	0.096484	-0.005873	-0.057631	0.104872	-0.180711
	(0.09844)	(0.04891)	(0.08097)	(0.03616)	(0.38751)	(0.22252)	(0.12668)
	[-0.98003]	[0.64582]	[1.19157]	[-0.16243]	[-0.14872]	[0.47129]	[-1.42651]
R-squared	0.759820	0.607669	0.789715	0.539441	0.623619	0.600646	0.496728
Adj. R-squared	0.519640	0.215338	0.579429	0.078882	0.247238	0.201291	-0.006544
Sum sq. resids	0.673607	0.166244	0.455721	0.090865	10.43747	3.441685	1.115452
S.E. equation	0.211913	0.105275	0.174303	0.077831	0.834165	0.479005	0.272697
F-statistic	3.163547	1.548869	3.755443	1.171276	1.656884	1.504042	0.986998

ISSN NUMBER: 1116-249X

Log likelihood	15.36389	37.05135	21.42078	46.41455	-27.11402	-9.917690	7.546181
Akaike AIC	0.041039	-1.358152	-0.349727	-1.962229	2.781550	1.672109	0.545408
Schwarz SC	0.781162	-0.618029	0.390395	-1.222107	3.521672	2.412231	1.285530
Mean dependent	0.036908	-0.004712	0.116737	-0.016088	-0.042240	0.019148	-0.017711
S.D. dependent	0.305756	0.118846	0.268772	0.081095	0.961442	0.535977	0.271809

Determinant resid covariance dof adj.)	1.16E-13
Determinant resid covariance	7.23E-16
Log likelihood	232.4709
Akaike information criterion	-7.320703
Schwarz criterion	-1.816042
Number of coefficients	119

The VECM short-run model (Table 9) captures dynamic adjustments toward long-run equilibrium, with the error correction term (CointEq1) for GDP growth (D(LNGDP)) being significant and negative (-0.182, t = -4.31), confirming convergence at an 18.2% speed of adjustment per period. Short-run dynamics reveal that industrial output (LNIND) and CO2 emissions (LNC02) exhibit lagged effects on GDP, with mixed significance across periods. Exchange rate (LNEXR) changes show immediate negative impacts on GDP (-0.661, t = -4.45) but positive lagged effects, while inflation (LNINFLARATE) and interest rates (LNINTRATE) display volatile short-run influences. Trade openness (LNTO) has a negative contemporaneous effect on GDP (-0.457, t = -2.28) but positive lagged spillovers. The model's moderate R^2 values (0.54–0.79) suggest varying explanatory power across equations, with GDP and exchange rate adjustments being the most robust. The system's overall diagnostics (e.g., log likelihood = 232.47, Akaike = -7.32) indicate reasonable fit, though some variables show weak short-run significance, highlighting the dominance of long-run equilibrium forces.

Discussion of Results

The empirical findings consistently show that several macroeconomic variables exert both short-run and long-run influences on Nigeria's GDP, though the magnitude and direction of these effects

ISSN NUMBER: 1116-249X

vary across estimation techniques. The FMOLS results highlight carbon emissions as a major long-run determinant of GDP, showing a strong negative relationship. This indicates that rising environmental degradation undermines productive capacity and overall economic performance. Inflation also exhibits a mild negative association, reflecting how price instability erodes purchasing power, discourages investment, and reduces output. On the other hand, variables such as exchange rate, industrial output, interest rate, and trade openness are insignificant in the FMOLS framework, suggesting that their long-run effects may be indirect or overshadowed by structural rigidities in the economy.

The ARDL model enriches this understanding by revealing strong short-run dynamics in GDP behavior. Exchange rate depreciation demonstrates an immediate contractionary effect on GDP, while interest rates similarly reduce output in the short run, reflecting the sensitivity of economic activity to monetary policy and external sector fluctuations. Inflation, however, shows some positive short-run effects, implying that mild inflationary pressures may accompany periods of increased expenditure or economic expansion. Trade openness emerges as a positive short-run contributor, suggesting gains from international transactions, although these effects appear unstable across lags. The error correction component confirms that the system adjusts steadily toward long-run equilibrium, emphasizing the persistence of structural economic relationships identified in the long-run ARDL estimates.

The VECM results provide further confirmation of a stable long-run relationship among the variables. In this framework, carbon emissions and industrial output emerge as strong long-run drivers of GDP, implying that environmental quality and industrial performance are central to sustained economic growth. Exchange rate depreciation, inflation, and trade openness exert long-run negative effects, indicating that macroeconomic instability and external sector distortions weaken growth fundamentals over time. The positive long-run effect of interest rates in the VECM model suggests that, beyond a certain threshold, efficient financial intermediation and improved returns on investment may stimulate productive activities. The short-run VECM results also show that GDP responds strongly to deviations from long-run equilibrium, adjusting through the influence of exchange rates, inflation, and other monetary factors. Collectively, the models reveal that GDP in Nigeria is shaped by a complex interaction of real, monetary, environmental, and

ISSN NUMBER: 1116-249X

external sector variables, with short-run fluctuations ultimately converging to a stable long-run growth path.

4.0 Conclusion

The results reveal that Nigeria's macroeconomic and environmental indicators exhibit both short-run volatility and long-run equilibrium relationships. In the long run, CO_2 emissions negatively impact GDP, while inflation and trade openness have positive effects. Exchange rates and interest rates drive short-term fluctuations, with exchange rates showing immediate negative effects but lagged positive adjustments. The error correction models confirm a stable long-run equilibrium, with GDP adjusting to fundamental economic forces, though short-run dynamics are influenced by monetary policy, trade openness, and environmental factors. Industrialization and CO_2 emissions play dominant roles in shaping economic growth, while inflation and exchange rate volatility pose significant challenges.

5.0 Recommendations

i. Reduce reliance on oil by boosting non-oil sectors like agriculture and manufacturing to stabilize GDP growth and mitigate exchange rate volatility.

ii. Implement cleaner technologies and regulations to curb CO_2 emissions, as high emissions negatively impact long-run economic performance.

iii. Adopt tighter monetary policies and fiscal discipline to manage inflation spikes, which destabilize short-run economic conditions.

iv. Enhance foreign exchange management through reserves accumulation and reduced import dependency to minimize exchange rate shocks.

v. Encourage export diversification and regional trade agreements to harness the positive long-run benefits of trade on GDP.

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