Effect of Demographic and Socioeconomic Dynamics on PM2.5 in Nigeria

[1]Fiala, T., [2]Momodu, A. A., [3]Nwikina, C.G & [4]Njoku, K.C
Department of Economics,
[1,2,3,&4]Rivers State University, Port Harcourt,
Rivers State, Nigeria.
tuboalabo.fiala@ust.edu.ng
https://doi.org/10.56201/ijssmr.vol.12no10.2026.pg379.391

Abstract
This study examines the effects of demographic and socioeconomic dynamics on PM2.5 air pollution in Nigeria over the period 1990–2024. Annual data were sourced from the World Development Indicators (WDI), covering population growth, urbanization, GDP per capita growth, energy consumption per capita, and PM2.5 exposure. The study employs descriptive statistics, the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) unit root test, ARDL bounds testing, ARDL estimation, and residual diagnostic tests. The results indicate a mixture of I(0) and I(1) variables, supporting the suitability of the ARDL approach. The estimation results reveal significant short-run effects of population growth, GDP per capita growth, and energy consumption on PM2.5, although their effects vary across lags. In the long run, the coefficients of population growth, urbanization, GDP per capita growth, and energy consumption are statistically insignificant. The diagnostic results indicate no evidence of serial correlation, heteroskedasticity, or non-normality in the residuals. The study concludes that Nigeria's particulate pollution is influenced primarily by short-run demographic and socioeconomic dynamics and recommends cleaner energy use, sustainable urban development, and environmentally compatible economic growth to improve air quality.

Keywords: *PM2.5; population growth; urbanization; GDP per capita; energy consumption; ARDL; Nigeria.*

1. Introduction

Demographic and socioeconomic transformations are important determinants of environmental quality, particularly in developing economies experiencing rapid population growth and urbanization. Population expansion increases demand for housing, transportation, energy and other resources, while urbanization concentrates people and economic activities in ways that may intensify air pollution. Economic growth and energy consumption can further amplify these pressures through increased production, mobility and resource use, although higher incomes may also facilitate cleaner technologies and improved environmental management. These competing mechanisms make the relationship between demographic and socioeconomic dynamics and environmental quality an important empirical question. PM2.5 is particularly relevant because fine particulate pollution is closely associated with adverse health outcomes and substantial economic costs. Nigeria provides an important setting for examining this relationship. According to the World Bank's World Development Indicators (WDI), Nigeria's population increased from approximately 97.1 million in 1990 to 232.7 million in 2024, while the share of the population living in urban areas increased from 35.2% to 63.0% over the same period (World Bank, 2026). This demographic and urban transformation has occurred

alongside continuing economic and energy demands. Yet the environmental consequences remain substantial: Nigeria's mean annual PM2.5 exposure was approximately 56.5 μg/m³ in 2020, according to World Bank data. The significance of this pollution burden extends beyond environmental quality. In Lagos, ambient air pollution was estimated to have caused approximately 11,200 premature deaths and US$2.1 billion in health-related economic losses in 2018 (Croitoru et al., 2020).

Theoretically, these relationships can be understood through complementary perspectives. The STIRPAT framework links environmental impact to population, affluence and technology, providing an overarching basis for examining demographic, economic and energy-related determinants of pollution (Ehrlich & Holdren, 1971; Dietz & Rosa, 1994, 1997). The Environmental Kuznets Curve (EKC) proposes that environmental degradation may initially increase with economic development before declining beyond a potential income threshold (Grossman & Krueger, 1995). The Urban Environmental Transition perspective further suggests that urbanization alters environmental pressures through changes in population concentration, production, consumption, infrastructure and resource use (McGranahan & Satterthwaite, 2003). Together, these perspectives suggest that PM2.5 in Nigeria may reflect the interaction of demographic expansion, urbanization, economic activity and energy consumption.

Despite the relevance of these mechanisms, the combined effects of these demographic and socioeconomic dynamics on PM2.5 in Nigeria remain insufficiently established. In particular, limited attention has been given to examining population growth, urbanization, GDP per capita growth and energy consumption per capita within a unified empirical framework. This represents an important gap because demographic expansion does not necessarily translate into environmental pressure independently of the urban, economic and energy structures through which it occurs.

Against this background, this study examines the effects of demographic and socioeconomic dynamics on PM2.5 in Nigeria, using population growth and urbanization as demographic indicators and GDP per capita growth and energy consumption per capita as socioeconomic and energy-related indicators. By focusing specifically on PM2.5, the study provides evidence on the mechanisms through which Nigeria's demographic and socioeconomic transformation is associated with particulate pollution and to contribute empirical evidence relevant to policies aimed at reconciling demographic and economic development with improved environmental quality.

2. Literature Review

Theoretical Framework

2.1 Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT)

The IPAT framework, associated with Ehrlich and Holdren (1971), conceptualizes environmental impact as a multiplicative function of population, affluence and technology: (I=P\times A\times T). Its central assumption is that environmental pressure arises from the combined effects of demographic scale, economic activity per person, and the environmental intensity of prevailing production and consumption technologies. However, the deterministic structure of IPAT imposes proportional relationships among these components and therefore provides limited scope for statistical hypothesis testing. Dietz and Rosa (1994, 1997) subsequently developed the STIRPAT formulation, which expresses environmental impact stochastically as a function of population, affluence and technology and permits the magnitude of each determinant to be estimated empirically.

The principal assumption of STIRPAT is that changes in demographic, economic and technological conditions produce measurable changes in environmental impact, while the magnitude of these effects need not be proportional. This makes the framework particularly suitable for examining heterogeneous environmental responses across countries and over time. Dietz and Rosa (1997), for example, demonstrated that population effects need not conform to the strict proportionality implied by the original IPAT identity.

For the present study, STIRPAT provides the principal theoretical foundation for examining PM2.5 pollution in Nigeria. Population growth represents demographic pressure, GDP per capita growth captures the economic or affluence dimension, while energy consumption per capita represents an important channel through which production and consumption activities generate environmental pressure. Urbanization is incorporated as an additional demographic-structural factor because population concentration can modify energy demand, transportation requirements and economic activity. PM2.5 therefore represents the environmental impact component of the framework. The theory consequently provides a coherent basis for investigating whether Nigeria's demographic and socioeconomic transformation has contributed to changes in particulate pollution.

2.2 Environmental Kuznets Curve (EKC)

The Environmental Kuznets Curve is principally associated with Grossman and Krueger (1995), who examined the relationship between per-capita income and several indicators of environmental quality. The central assumption of the EKC is that environmental degradation does not necessarily increase monotonically with economic development. Rather, pollution may initially increase as economies expand and industrialize but, after a potential income threshold, decline as cleaner technologies, structural economic changes, environmental regulation and demand for environmental quality become increasingly important. Grossman and Krueger found evidence of an inverted-U relationship for several environmental indicators, although the turning point varied across pollutants.

The relevance of the EKC to this study lies principally in the relationship between economic development and PM2.5. Economic expansion may initially increase particulate pollution through increased production, transportation, energy demand and consumption. At higher levels of development, however, technological improvements, changes in economic structure and stronger environmental management may reduce pollution intensity. The EKC therefore provides a complementary theoretical explanation for why the effect of economic development on PM2.5 may be nonlinear rather than uniformly positive or negative.

2.3 Urban Environmental Transition Perspective

The Urban Environmental Transition perspective, associated with the work of McGranahan and Satterthwaite (2003), emphasizes the environmental implications of the increasing concentration of population, production and consumption in urban areas. Its central assumption is that urbanization changes the scale, composition and spatial organization of environmental pressures. Urban growth can increase demand for energy, transportation, housing, infrastructure and other resources, thereby intensifying environmental pressures; however, urban concentration can also create opportunities for more efficient infrastructure and service provision. Consequently, the environmental effects of urbanization depend substantially on the form and management of urban development.

This perspective is particularly relevant to Nigeria, where rapid urbanization is occurring alongside population growth and increasing demand for energy and urban services. Urbanization can influence PM2.5 through several interconnected channels, including transportation, household and commercial energy consumption, industrial activity and the

concentration of economic activities. At the same time, greater population density may facilitate more efficient transportation systems, infrastructure provision and environmental regulation. Thus, the Urban Environmental Transition perspective does not imply that urbanization is inherently environmentally harmful; rather, it suggests that its environmental consequences depend on the structure and management of urban growth.

Within this study, the perspective provides the principal theoretical justification for incorporating urbanization rate as an explanatory variable alongside population growth. It complements STIRPAT by elaborating the demographic and spatial mechanisms through which population redistribution toward urban areas can affect PM2.5. The perspective is therefore particularly useful for interpreting the environmental consequences of Nigeria's ongoing urban transition.

Empirical Review

Zuo and Shi (2020) utilized a Bayesian hierarchical spatial quantile regression method to explore the effect of socioeconomic activity on $PM_{2.5}$air pollution. By introducing spatial random effects into the model, the researchers significantly reduced the spatial autocorrelations of residuals. The empirical study demonstrated that $PM_{2.5}$concentration levels were strongly correlated with total population, urbanization rate, industrialization level, and energy efficiency at all quantiles. For upper quantiles, the impact of the urbanization rate on haze was the greatest among all the predictors, followed by total population; while for lower quantiles, industrialization exerted the greatest impact on $PM_{2.5}$concentration. The impacts of energy efficiency in the lower 15 % and upper 15 % quantiles were higher compared with any of the other quantiles.

Bildirici and Kayıkçı (2023) investigated the dynamic and causal relationship among energy intensity, economic growth, urbanization, energy consumption, foreign direct investment, and $PM_{2.5}$in China, India, Germany, Canada, the USA, and the United Kingdom over the 1995–2019 period through the panel Fourier bootstrapping ARDL (PFBARDL) model and the panel Fourier causality test. According to the PFBARDL results, the study detected evidence of cointegration between the variables. In the PFBARDL model, the error correction coefficient was determined as −0.169. The results showed bidirectional causality between economic growth and $PM_{2.5}$release, between foreign direct investment and $PM_{2.5}$release, and between energy intensity and $PM_{2.5}$release. Rising economic growth, energy consumption structure, and urbanization exerted adverse effects on $PM_{2.5}$concentrations.

Yang et al. (2022) examined economic determinants of $PM_{2.5}$ concentrations and incorporated the spatial spillover effect of bank credit by employing the spatial Durbin model (SDM) under the stochastic impacts by regression on population, affluence, and technology framework. Using China's provincial dataset from 1998 to 2016, the main findings were as follows: first, evidence existed in support of spatial dependence of $PM_{2.5}$ concentrations and their inverted U-shaped relationship with economic growth in China; second, $PM_{2.5}$ concentrations in a province tended to increase as the level of its own urbanization increased, but they decreased as its own human capital and bank credit increased, while the level of neighboring urbanization positively influenced a province's $PM_{2.5}$ concentrations, whereas neighboring population size, industrialization, trade openness, and bank credit presented negative impacts; and third, indirect effects of the SDM indicated a significant and negative spatial spillover effect of bank credit on $PM_{2.5}$ concentrations.

Aninwagu and Nyeche (2024) investigated the impact of renewable energy consumption, forest area, and economic growth on CO_2 emissions in Nigeria. They used renewable energy consumption (REC), forest area as a percentage of land area (FOA), and GDP per capita (GDPC) as independent variables, while CO_2 emissions served as the dependent variable.

Time-series data for these variables came from the World Development Indicators (WDI) for the period 1990 to 2023. The analytical methods employed included unit root tests, the Engle-Granger cointegration test, error correction model analysis, and residual diagnostic tests. The augmented Dickey-Fuller (ADF) unit root test results indicated that all variables were integrated of order one, I(1). The error correction model results established a statistically significant and negative relationship between REC and CO_2 emissions. Furthermore, the analysis revealed a positive but statistically non-significant relationship between FOA and CO_2 emissions. Additionally, GDP per capita showed a positive but statistically non-significant effect on CO_2 emissions.

Park et al. (2021) analyzed the characteristics of indoor PM generation by activities in a residential building and the removal effect of the ventilation methods. The researchers accomplished field measurements for indoor PM generation activities in real conditions, such as vacuum cleaning, cooking (fish and pork), air freshener spraying, and scented candle burning in a residential building. As a result, the PM concentration was the highest for broiling fish, with a concentration of 15.714 mg/m³ for PM_{10} and 13.679 mg/m³ for $PM_{2.5}$. The decreasing order of the peak concentration for indoor activities was cooking, burning scented candles, vacuuming, and spraying air freshener. In addition, the residual PM concentration exceeded the standard upper limit even 30 minutes after most of the PM generation activities had ended. Especially in the cooking activity, which possessed the highest PM generation, PM could not be removed properly even when the range hood was operated.

Yang et al. (2022) examined economic determinants of $PM_{2.5}$ concentrations and incorporated the spatial spillover effect of bank credit by employing the spatial Durbin model (SDM) under the stochastic impacts by regression on population, affluence, and technology framework. Using China's provincial dataset from 1998 to 2016, the main findings were as follows: first, evidence existed in support of spatial dependence of $PM_{2.5}$ concentrations and their inverted U-shaped relationship with economic growth in China; second, $PM_{2.5}$ concentrations in a province tended to increase as the level of its own urbanization increased, but they decreased as its own human capital and bank credit increased, while the level of neighboring urbanization positively influenced a province's $PM_{2.5}$ concentrations, whereas neighboring population size, industrialization, trade openness, and bank credit presented negative impacts; and third, indirect effects of the SDM indicated a significant and negative spatial spillover effect of bank credit on $PM_{2.5}$ concentrations.

Zhang et al. (2022) developed a STIRPAT-scenario analysis framework by employing panel data from 11 cities in Zhejiang Province between 2006 and 2020 in order to predict the changing trend of $PM_{2.5}$ concentrations under five alternative scenarios. The results revealed that (1) urbanization development (P), economic development (A), technological innovation investment (T), and environmental regulation intensity exerted a significant inhibitory effect on $PM_{2.5}$ concentration in Zhejiang Province, while industrial structure, industrial energy consumption, and the number of motor vehicles (TR) exerted a significant increase on $PM_{2.5}$ concentration; (2) under any scenario the $PM_{2.5}$ concentration of 11 cities in Zhejiang Province could reach the constraint target set in the 14th Five-Year Plan, and the improvement in urban $PM_{2.5}$ quality was most obviously impacted by the high-quality development scenario (S4); and (3) toward 2035 $PM_{2.5}$ concentrations of 11 cities in Zhejiang Province could reach the National Class I level standard in most scenario models, among which Hangzhou, Jiaxing, and Shaoxing were under high pressure to reduce emissions and were the key areas for $PM_{2.5}$ management in Zhejiang Province, although most cities could not reach the 10 μg/m³ limit of WHO's AQG2005 version.

Khan and Bounnade (2024) examined the links between green investment, digitalization, renewable energy, export, and economic growth for a total of 30 Organisation for Economic

Co-operation and Development economies over the period between 1990 and 2020 in order to empirically probe the magnitude and the effect of green investment, economic growth, digitalization, export, and renewable energy on $PM_{2.5}$ air pollution. The researchers evaluated the panel for numerous diagnostic tests, including a long-run cointegration link that was acknowledged among the variables under investigation. The superior econometric estimation method of moment quantiles regression validated that economic growth was inimical, while green investment, renewable energy, export, and digitalization illustrated heterogeneous effects on $PM_{2.5}$ air pollution. On the basis of the findings, it was found that, excluding economic growth, the explanatory variables effectively reduced $PM_{2.5}$ air pollution in the Organisation for Economic Co-operation and Development countries. Nonetheless, the extent of green investment increase raised a proper inquiry that portrayed a mitigating trend across the quantiles.

3. Methodology

This study adopts a quantitative, longitudinal (time-series) research design. The data for this study was sourced from the World Bank's World Development Indicators (WDI) from 1990 to 2024. The few missing $PM_{2.5}$ data were completed using the linear interpolation.

The study was theoretically anchored on the STIRPAT model, which extends the deterministic IPAT identity (Impact = Population × Affluence × Technology).

The study specifies the following models:

$CO_2 = f(POPG, URB, GDPPC, ENEC)$ 3.1

$$PM2.5_t = \beta_0 + \beta_1 POPG + \beta_2 URB_t + \beta_3 GDPPC_t + \beta_4 ENEC_t + \mu_t \quad 3.2$$

$$\Delta PM2.5_t = \alpha_0 + \sum_{i=1}^{p} \alpha_1 \Delta PM2.5_{t-1} + \sum_{i=1}^{q} \alpha_2 \Delta POPG_{t-1} + \sum_{i=1}^{q} a_3 \Delta URB_{t-1} + \sum_{i=1}^{q} a_4 \Delta GDPPC_{t-1} + \sum_{i=1}^{q} a_5 \Delta ENEC_{t-1} + \lambda_1 PM2.5_{t-1} + \lambda_2 POPG_{t-1} + \lambda_3 URN_{t-1} + \lambda_4 GDPPC_{t-1} \lambda_5 ENEC_{t-1} + \varepsilon_{1t} \quad 3.3$$

Where:

$PM_{2.5t}$ = Particulate Matter (PM2.5) Air Pollution

POPG = Population growth rate (annual percentage change or total population)

URB = Urbanization rate (percentage of population residing in urban areas)

GDPPC = Gross domestic product (GDP) per capita growth

ENEC = Energy consumption per capita (kg of oil equivalent)

μ_t = stochastic error terms

Where: α_0 = constant parameter to be estimated; $\alpha_1 - \alpha_5$ = short run parameters; λ_1 - λ_5 = long-run multipliers; p = optimal lag for each of the dependent variables; q = optimal lag of the independent variables; Δ = first difference operator; ε_{1t} = error terms.

A priori expectation

$PM_{2.5t}$ = $\beta_1 > 0$, $\beta_2 < 0$, $\beta_3 > 0$, $\beta_4 > 0$.

4. Data Analysis

Table 4.1: Summary of Descriptive Statistics for the Variables

	ENEC	GDPPC	PM2_5	POPG	URB
Mean	303.8629	1.432857	59.39516	2.572857	49.10971
Median	299.1550	1.920000	61.58000	2.640000	49.24000
Maximum	376.5500	12.21000	77.12000	2.800000	62.98000

			48.1400		35.1900
Minimum	256.9200	-8.340000	0	2.080000	0
			6.91853		8.43804
Std. Dev.	30.74349	3.934968	0	0.237333	1
					-
			0.12402		0.01463
Skewness	0.451558	0.109973	8	-1.131566	3
			2.69430		1.78050
Kurtosis	2.338786	3.886862	1	2.849443	7
			0.20018		2.17002
Jarque-Bera	1.774834	1.217562	8	7.502295	8
			0.90475		0.33789
Probability	0.411718	0.544014	2	0.023491	7
			1841.25		1718.84
Sum	10331.34	50.15000	0	90.05000	0
Sum Sq.			1435.98		2420.81
Dev.	31190.35	526.4551	2	1.915114	8
Observation					
s	34	35	31	35	35

Source: *Author's computation using E-views 12 software (2026)*

The descriptive statistics presented in Table 4.1 indicate considerable differences in the distribution and scale of the variables over the study period. Energy consumption per capita (ENEC) recorded a mean value of 303.86 kg of oil equivalent per capita, while GDP per capita growth (GDPPC) averaged 1.432%. ENEC ranged from 256.9 minimum to 376.5 maximum. GDP per capita growth ranged from −8.340% to 12.210%, indicating substantial fluctuations in Nigeria's economic performance during the study period. Similarly, mean annual exposure to PM2.5 averaged 59.395 μg/m³, with values ranging from 48.140 to 77.120 μg/m³, suggesting a persistently high level of particulate pollution over the period.

Population growth (POPG) averaged 2.572% annually, ranging from 2.089% to 2.800%, indicating relatively sustained demographic expansion. The urbanization rate (URB) recorded a mean of 49.109%, with a minimum of 35.190% and a maximum of 62.980%, reflecting the substantial transformation of Nigeria's population distribution toward urban areas.

The standard deviations indicate relatively limited dispersion around the respective means for most variables, whereas GDP per capita growth exhibits greater variability relative to its mean, reflecting fluctuations in economic performance. The Jarque–Bera statistics further indicate that the null hypothesis of normality cannot be rejected at the 5% significance level where the associated probability values exceed 0.05. Thus, the variables can be considered approximately normally distributed based on the Jarque–Bera test.

Table 4.3 KPSS Unit Root Test

Variables	KPSS at Level	Critical value 5%	KPSS at 1st Diff.	Critical value 5%	Order of Integration
ENEC	0.517749	0.463000	0.061019	0.463000	1(1)
GDPPC	0.156907	0.463000	NA	NA	1(0)
PM2_5	0.322512	0.463000	NA	NA	1(0)
POPG	0.390428	0.463000	NA	NA	1(0)

URB	0.699101	0.463000	0.169709	0.463000	1(1)

Source: Researcher's computation using Eviews 12, (2026).

The results of the KPSS stationarity test presented in Table 4.3 indicate that energy consumption per capita (ENEC) and urbanization rate (URB) are non-stationary at level. Specifically, their KPSS statistics of 0.517749 and 0.699101, respectively, exceed the 5% critical value of 0.463000. Since the KPSS test has stationarity as its null hypothesis, these results imply rejection of the null hypothesis of level stationarity at the 5% significance level, providing evidence that ENEC and URB contain a unit-root process at level. However, after first differencing, the KPSS statistics decline to 0.061019 for ENEC and 0.169709 for URB, both of which are below the 5% critical value. The null hypothesis of stationarity can therefore not be rejected for the first-differenced series, indicating that both variables become stationary after first differencing and are consequently integrated of order one, I(1).

In contrast, the remaining variables exhibit KPSS statistics below the relevant 5% critical value in their level forms, indicating that their null hypotheses of stationarity cannot be rejected. These variables are therefore classified as I(0). Overall, the results establish that the variables comprise a mixture of I(0) and I(1) processes, with none appearing to be integrated beyond order one. The KPSS results in this study are also broadly consistent with the empirical evidence reported by Aninwagu et al. (2024), who obtained a mixture of I(0) and I(1) variables using the KPSS approach in their Nigerian study.

Table 4.3: Bounds Cointegration Tests Results for the Models

	F-STATISTICS	K	Critical value Lower bound 5%	Critical value Upper bound 5%
PM2.5	7.070220	4	2.56	3.49

Source: Researcher's computation using Eviews 12, (2026).

Note: K denotes number of explanatory variables

The results of the bounds test presented in Table 4.3 offer strong evidence of a statistically significant long-term relationship between the dependent and independent variables. The calculated F-statistic of 7.070220 surpasses both the lower and upper critical values at the 5 percent significance level.

Model estimation

Table 4.5: ARDL short and long run result of Particulate Matter (PM2.5)

Dependent Variable: PM2.5

Short run results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(PM2_5(-1))	0.581196	0.107564	5.403260	0.0326
D(PM2_5(-2))	0.791380	0.129741	6.099692	0.0258
D(PM2_5(-3))	-0.759414	0.149630	-5.075294	0.0367
D(POPG)	-217.4598	32.90727	-6.608258	0.0221
D(POPG(-1))	586.1527	61.28891	9.563766	0.0108
D(POPG(-2))	-63.84381	40.73784	-1.567187	0.2576
D(POPG(-3))	-105.7158	27.96867	-3.779792	0.0634
D(URB)	205.5713	60.38644	3.404263	0.0765
D(URB(-1))	537.1855	120.1106	4.472422	0.0465

D(URB(-2))	-281.2528	112.4200	-2.501804	0.1295
D(URB(-3))	452.0067	65.38842	6.912641	0.0203
D(GDPPC)	-2.950261	0.299859	-9.838822	0.0102
D(GDPPC(-1))	5.614027	0.505444	11.10712	0.0080
D(GDPPC(-2))	5.094607	0.466016	10.93225	0.0083
D(GDPPC(-3))	2.471702	0.272405	9.073634	0.0119
D(ENEC)	0.202894	0.032822	6.181619	0.0252
D(ENEC(-1))	-0.553113	0.055037	-10.04985	0.0098
D(ENEC(-2))	-0.313465	0.040295	-7.779218	0.0161
D(ENEC(-3))	-0.340560	0.033718	-10.10020	0.0097
CointEq(-1)*	-2.081327	0.170810	-12.18502	0.0067

Long run results

Variable	Coefficient	Std. Error	t-Statistic	Prob.
POPG	8.304965	71.51988	0.116121	0.9182
URB	-0.375307	0.715799	-0.524319	0.6524
GDPPC	-4.537115	4.867764	-0.932074	0.4497
ENEC	0.353501	0.236555	1.494368	0.2737
C	-402.0215	506.1005	-0.794351	0.5103

R-squared 0.974981; Adjusted R-squared 0.907073

Source: Researcher's computation using Eviews 12, (2026).

The ARDL results presented in Table 4.4 reveal both short-run dynamics and long-run relationships between PM2.5 exposure and the demographic and socioeconomic variables in Nigeria. The estimated coefficients indicate that the effects of the explanatory variables differ across time horizons, suggesting that demographic and socioeconomic changes may exert immediate effects on particulate pollution that differ from their longer-term equilibrium effects. In the **short run**, population growth (POPG) has a negative and statistically significant effect on PM2.5 in the current period, whereas its second and third lags remain negative but statistically insignificant. In contrast, the first lag of population growth is positive and statistically significant, with a coefficient of 586.15, indicating that an increase in population growth is associated with a substantial increase in PM2.5 exposure after one period, ceteris paribus. In the long run, population growth has a positive but statistically insignificant coefficient of 8.304, suggesting that population growth is associated with higher PM2.5 exposure in equilibrium, although the evidence is insufficient to conclude that the effect differs statistically from zero. The positive long-run sign is broadly consistent with the STIRPAT framework, which identifies population as a fundamental determinant of environmental pressure (Dietz & Rosa, 1997), and is also consistent with empirical evidence reported by Lim et al. (2020).

Urbanization (URB) exhibits mixed short-run dynamics. Its first and third lags have positive but statistically insignificant coefficients of 537.18 and 452.00, respectively, whereas its second lag has a negative and statistically insignificant coefficient. Thus, although the signs vary across lags, none of the reported lagged urbanization effects is statistically distinguishable from zero. In the long run, urbanization has a negative and statistically insignificant coefficient of −0.375, implying an inverse but statistically weak association between urbanization and PM2.5 exposure. The negative sign is consistent with the possibility that urban concentration may generate efficiency gains through infrastructure, transportation and service provision,

although the absence of statistical significance means that this interpretation should be treated cautiously. The result is broadly consistent with the evidence reported by Wei et al. (2021).

GDP per capita growth (GDPPC) also exhibits different short- and long-run effects. In the short run, its contemporaneous coefficient is negative but statistically insignificant, whereas its first, second and third lags are positive and statistically significant, with coefficients of 5.614, 5.094 and 0.247, respectively. These results suggest that economic expansion may exert delayed upward pressure on PM2.5 exposure in the short term. In contrast, the long-run coefficient is negative (−4.537) but statistically insignificant, indicating an inverse but statistically inconclusive relationship between GDP per capita growth and PM2.5 in the long run. Although the negative sign does not conform to the study's initial expectation of a positive association, it is compatible with the possibility that longer-term economic development may be accompanied by structural or technological changes that reduce pollution intensity. The result is broadly comparable with the findings of Hussain et al. (2025).

Energy consumption per capita (ENEC) has a positive and statistically significant contemporaneous effect on PM2.5, with a coefficient of 0.202, indicating that an increase in energy consumption per capita is associated with an increase in PM2.5 exposure in the short run, ceteris paribus. Its first, second and third lags are negative and statistically significant, suggesting that the effect of energy consumption is dynamic and reverses sign over subsequent periods. In the long run, however, energy consumption has a positive coefficient of 0.353, although the effect is statistically insignificant. Thus, while the estimated long-run sign is consistent with the expectation that greater energy consumption contributes to particulate pollution, the evidence does not establish a statistically significant long-run effect. The positive association is consistent with the findings of Liu et al. (2024).

The estimated error-correction coefficient, CointEq(−1) = −2.081327, is negative and indicates a strong adjustment mechanism in the estimated ARDL specification. The model records an R^2 of 0.974981, indicating that approximately 97.5% of the in-sample variation in PM2.5 is explained by the regressors and lagged terms included in the model. The adjusted R^2 of 0.907073 indicates that approximately 90.7% of the variation is explained after accounting for the number of estimated parameters. These statistics indicate a high in-sample explanatory fit, although they should not, by themselves, be interpreted as evidence of model robustness.

Table 4.5: Post-Estimation Tests Results

Test	Null Hypothesis	F-Statistic	Probability	Decision
Serial Correlation LM Test	**H_0:** No serial correlation	0.026295	0.9741	Retain H_0
Heteroskedasticity Test	**H_0:** Homoscedasticity	1.716117	0.1522	Retain H_0
Normality Test	**H_0:** Normally distributed	0.374736	0.829138	Retain H_0

Source: *Researcher's Computation using Eviews 12, 2026.*

The post-estimation diagnostic results reported in Table 4.5 provide evidence that the residuals of the estimated ARDL model satisfy several important diagnostic conditions. The Breusch–Godfrey LM test produces a statistic of 0.026295 with a probability value of 0.9741. Since the probability value exceeds the 5% significance level, the null hypothesis of no serial correlation cannot be rejected. This indicates that there is no statistical evidence of serial correlation in the model residuals and provides support for the adequacy of the model's dynamic specification.

The Breusch–Pagan–Godfrey heteroskedasticity test reports a probability value of 0.1522, which is also greater than 0.05. Accordingly, the null hypothesis of homoskedasticity cannot be rejected, indicating that there is no statistical evidence of heteroskedasticity in the residuals.

This suggests that the variance of the disturbances does not systematically vary with the explanatory variables and supports the use of the conventional standard errors reported for the estimated model.

The Jarque–Bera normality test yields a statistic of 0.374736 with a probability value of 0.829138. Since the probability value exceeds 0.05, the null hypothesis that the residuals are normally distributed cannot be rejected. The residuals can therefore be regarded as consistent with normality at the 5% significance level.

Taken together, the diagnostic results provide no evidence of residual serial correlation, heteroskedasticity, or non-normality at the 5% significance level. These findings support the adequacy of the estimated ARDL model with respect to the specific residual properties examined.

5. Conclusion and Recommendations

Conclusion

This study examined the effects of demographic and socioeconomic dynamics on PM2.5 in Nigeria using the ARDL approach. The findings reveal that population growth, GDP per capita growth and energy consumption per capita exert significant effects on PM2.5 at selected short-run periods, while their long-run effects, alongside that of urbanization, are statistically insignificant. Energy consumption presents the clearest short-run pollution pressure, highlighting the importance of cleaner energy use and improved energy efficiency.

Overall, the findings suggest that Nigeria's particulate pollution is influenced by dynamic demographic and socioeconomic processes. Reducing PM2.5 therefore requires an integrated policy approach combining demographic and urban planning, cleaner energy transition, sustainable transportation and environmentally sustainable economic growth.

Recommendations

Based on the findings and conclusion drawn from this study, the following recommendations are made:

i. Government should promote energy efficiency and accelerate the deployment of cleaner electricity and distributed renewable-energy systems, while reducing reliance on highly polluting fossil-fuel-based generation and backup generators. This is consistent with evidence that energy-system reform can simultaneously improve air quality and strengthen energy security.

ii. Government should promote energy efficiency and accelerate the deployment of cleaner electricity and distributed renewable-energy systems, while reducing reliance on highly polluting fossil-fuel-based generation and backup generators. This is consistent with evidence that energy-system reform can simultaneously improve air quality and strengthen energy security.

iii. Government should strengthen mass-transit systems, improve vehicle-emission standards and inspection, and encourage cleaner vehicle technologies. This is particularly relevant because road transport is identified as a major source of PM2.5 in Lagos, alongside industrial emissions and generators.

iv. Government should strengthen mass-transit systems, improve vehicle-emission standards and inspection, and encourage cleaner vehicle technologies. This is particularly relevant because road transport is identified as a major source of PM2.5 in Lagos, alongside industrial emissions and generators.

References

Aninwagu, V. O., & Momodu, A. A. (2025). Healthcare resources and employment structure on female labor force participation in Nigeria. *International Journal of Research Publication and Reviews*, 6(6), 11406-11415. https://doi.org/10.55248/gengpi.6.0625.2357

Aninwagu, V. O., & Nyeche, E. (2025). *Impact of renewable energy consumption, forest area, and economic growth on CO_2 emissions in Nigeria*. http://dx.doi.org/10.2139/ssrn.5358945

Aninwagu, V. O., Onyema, J. I., Momodu, A. A., & Amadi, C. R. (2024). Gender inequality and socioeconomic development: An analysis of the effect on poverty in Nigeria. *International Journal of Economic Research and Development Studies (JERDS), 1*(1). https://ssrn.com/abstract=5358929

Aninwagu, V. O., Onyema, J. I., Momodu, A. A., & Amadi, C. R. (2025). Gender inequality and socioeconomic development: An empirical investigation of the effect on unemployment in Nigeria. *Journal of World Economics and Financial Report (JWEF), 1*(1), 205-220.

Bildirici, M. E., & Kayıkçı, C. F. (2023). Energy consumption, energy intensity, economic growth, FDI, urbanization, PM2.5 concentrations nexus. *Environment, Development and Sustainability*, 1-19

Croitoru, L., Chang, J. C., & Kelly, A. (2020). *The cost of air pollution in Lagos*. World Bank.

Dietz, T., & Rosa, E. A. (1994). Rethinking the environmental impacts of population, affluence and technology. *Human Ecology Review, 1*(2), 277–300.

Dietz, T., & Rosa, E. A. (1997). Effects of population and affluence on CO_2 emissions. *Proceedings of the National Academy of Sciences, 94*(1), 175–179. https://www.pnas.org/doi/10.1073/pnas.94.1.175

Ehrlich, P., & Holdren, J. (1971). Impact of population growth. *Science, 171,* 1212-1217.

Elliott, G., Rothenberg, T. J., & Stock, J. H. (1996). Efficient tests for an autoregressive unit Root. *Econometrica*, 64(4), 813–836

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The Quarterly Journal of Economics, 110*(2), 353–377.

Husain, S. A., Alim, W., Gull, H., Azeem, M. (2025). *Financial development and population growth as drivers of environmental change: Evidence from South Asia.* https://induspublishers.com/IJSS/article/view/721

Khan, Y. Z., & Bounade, C.D. (2024). Particulate matter 2.5 air pollution mitigation strategy: the role of green investment, digitalization, and renewable energy in the organization for economic co-operation and development (OECD) countries. *Clean Technologies and Environmental Policy, 27*, 1037 - 1051.

Lim, C., Ryu, J., Choi, S. Jeon, Woo-kyun Lee (2020). *Understanding global PM2.5 concentrations and their drivers in recent decades (1998-2016).* https://doi.org/10.1016/j.envint.2020.106011

Liu, Y., Shen, R., & Yao, L. (2024). *Characterization and regional linkage analysis of PM2.5 emissions driven by energy consumption in mainland China, 2007-2017.* https://doi.org/10.1016/j.jenvman.2024.123615

McGranahan, G., & Satterthwaite, D. (2003). Urban centers: An assessment of sustainability. *Annual Review of Environment and Resources, 28*, 243–274.

Onyema, J. I., Momodu, A. A., Amadi, R. C., & Aninwagu, V. O. (2024). Investment in infrastructural and economic growth in Nigeria from 1990 – 2022. *International Journal of Applied Economics, Agriculture and Management Sciences (IJAAMS), 2*(2), 149-163.

Park, S., Song, D., Park, S., & Choi, Y. (2021). Particulate matter generation in daily activities and removal effect by ventilation methods in residential building. *Air Quality, Atmosphere & Health, 14*, 1665 - 1680.

Pesaran, M. H., & Pesaran, B. (1997). *Microfit econometric software manual*. Oxford University Press.

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approach. *Journal of Applied Econometrics, 16*(3), 289–326. https://doi.org/10.1002/jae.616

Wei, G., Sun, P., Jiang, S., Shen, Y., Liu, B., Zhang, Z., & Ouyang, X. (2021). *The driving influence of multi-dimensional urbanization on PM2.5 concentrations in Africa: New evidence from multi-source remote sensing data, 2000–2018.* https://doi.org/10.3390/ijerph18179389

World Bank. (2026). *World Development Indicators*. World Bank.

Yang, F., Xu, Q., Li, K., Yuen, K.F., & Shi, W. (2022). The inhibition effect of bank credits on PM2.5 concentrations: Spatial evidence from high-polluting firms in China. *Environmental pollution*, 119639

Yang, F., Xu, Q., Li, K., Yuen, K.F., & Shi, W. (2022). The inhibition effect of bank credits on PM2.5 concentrations: Spatial evidence from high-polluting firms in China. *Environmental pollution*, 119639

Yang, F., Xu, Q., Li, K., Yuen, K.F., & Shi, W. (2022). The inhibition effect of bank credits on PM2.5 concentrations: Spatial evidence from high-polluting firms in China. *Environmental pollution*, 119639.

Zhang, Q., Ye, S., Ma, T., Fang, X., Shen, Y., & Ding, L. (2022). Influencing factors and trend prediction of PM2.5 concentration based on STRIPAT-Scenario analysis in Zhejiang Province, China. *Environment, Development and Sustainability*, 1 - 25.

Zou, Q., & Shi, J. (2020). The heterogeneous effect of socioeconomic driving factors on PM2.5 in China's 30 province-level administrative regions: Evidence from Bayesian hierarchical spatial quantile regression. *Environmental pollution, 264*.