Urbanization–Environment Nexus in Nigeria: Dynamic Econometric Evidence on Population Density, Industrial Activity, Waste Generation and Carbon Emissions

Olamide Gloria AKPOYOWARE and Callistar Kidochukwu OBI

Department of Economics, Faculty of the Social Sciences, Delta State University, Abraka, Delta State, Nigeria.
Corresponding Author Email: olamideoware@gmail.com

Direct Research Journal of Management and Strategic Studies

Vol. 7(2), Pp. 129-140, November 2026
Author(s) retains the copyright of this article
This article is published under the terms of the Creative Commons Attribution License 4.0.
Research Article
ISSN: 2787-009X

Received 18 August 2026, Accepted 30 October 2026, Published 4 November 2026

ABSTRACT

Background of the study: *Nigeria's rapid urban transition increases demand for housing, transport, energy and municipal services. Where infrastructure and environmental management lag, population concentration, industrial activity and waste generation may intensify carbon emissions.* ***Aim and objectives of the study:*** *This study examined the relationship between Urbanization and environmental degradation in Nigeria from 1990 to 2024. It assessed urban population, population density, industrial output and waste generation in relation to carbon dioxide (CO_2) emissions.* ***Methodology:*** *An ex-post facto design used annual secondary data for 1990–2024 (35 observations). The study applied the STIRPAT framework, Augmented Dickey–Fuller unit-root testing and the autoregressive distributed lag (ARDL) bounds approach.* ***Results:*** *The reported ADF results classified CO_2 emissions and waste generation as I(0), and urban population, population density and industrial output as I(1). The bounds-test statistic (F = 10.58627) exceeded the reported 5% upper bound (4.01), indicating a long-run relationship. Long-run population density (β = 1.170296, p = 0.0390) and waste generation (β = 0.357932, p < 0.001) were positive and significant. Urban population (β = −0.380512, p = 0.4461) and industrial output (β = −0.017187, p = 0.3783) were insignificant. In the short run, current and lagged changes in waste generation were negative and significant. The error-correction coefficient was −0.836582 (p = 0.0004). Implications for society and the research community: The findings support improved urban planning, municipal waste collection and treatment, and industrial emissions monitoring. They also highlight the need for transparent waste data, clearly defined indicators and robustness checks in future research.* ***Conclusion:*** *Population density and waste generation are the principal positive long-run correlates of CO_2 emissions in the reported model. Sustainable urban development requires integrated spatial planning and effective waste governance.*

Keywords: *Urbanization; environmental degradation; carbon dioxide emissions; population density; waste generation; STIRPAT; ARDL; Nigeria*



Citation: Akpoyoware, O. G. & Obi, C. K. (2026). Urbanisation–Environment Nexus in Nigeria: Dynamic Econometric Evidence on Population Density, Industrial Activity, Waste Generation and Carbon Emissions. Direct Research Journal of Management and Strategic Studies. Vol. 7(2), Pp. 129-140.
https://doi.org/10.4314/drjmss.v7i2.8

INTRODUCTION

Urbanization is a major demographic and spatial process characterized by an increasing proportion of the population living in towns and cities and the expansion of built-up areas. It can promote productivity, innovation, access to services and economic transformation. However, urban expansion also increases demand for electricity, transport,

housing, construction materials, water and municipal services. The environmental consequences depend on the energy mix, urban form, industrial structure, transport systems, infrastructure provision and the capacity of institutions to regulate pollution. Recent global studies show that urban CO_2 emissions are shaped by interacting demographic, spatial and technological processes rather than population growth alone (Luqman et al., 2023; Liu et al., 2024a; Yang et al., 2025).

Nigeria is experiencing sustained urban growth, driven by natural population increase, rural-to-urban migration and the concentration of economic opportunities in urban centres. The resulting pressure on housing, road networks, electricity, water supply, sanitation and waste services is particularly important where infrastructure provision does not keep pace with demographic change. These pressures can contribute to traffic-related emissions, inefficient energy use, open waste burning, uncontrolled dumping and the conversion of vegetated land to built-up areas. African urban sustainability research stresses that informality, service inequalities and governance constraints require locally grounded planning responses rather than the uncritical transfer of generic city models (Afinowi & Monkam, 2025; Yeyouomo & Asongu, 2024).

Urban population and population density are related but conceptually distinct. Urban population measures the number or share of people living in urban settlements, whereas population density measures the number of people per unit of land area. A growing urban population may increase aggregate energy and transport demand, but density can either increase or reduce emissions depending on the organisation of the city. High density may intensify congestion and pressure on services where infrastructure is inadequate; compact and well-serviced development may, by contrast, reduce travel distances and support efficient public transport. Global city-level evidence finds that density, urban extent and physical compactness have heterogeneous relationships with emissions, while urban form and public transport efficiency can influence the carbon consequences of sprawl (Luqman et al., 2023; Yang et al., 2025; Lyu et al., 2025; Wen et al., 2024).

Industrial activity is another potential source of emissions through fossil-fuel combustion, industrial processes, freight movement and energy demand. Nevertheless, the effect of industrial output is not necessarily uniform. It depends on the composition of industry, the efficiency of production technologies, the energy sources used and the enforcement of environmental standards. A national aggregate measure may conceal differences between manufacturing, construction, mining and oil-and-gas activities. Recent research indicates that urban expansion can influence emissions through industrial agglomeration and structural upgrading, while carbon performance also depends on the spatial and institutional context (Liu et al., 2024b; Zhang et al., 2024; Ma et al., 2024; Lohwasser et al., 2025). Waste generation is closely associated with urban consumption and production. Solid waste can contribute to greenhouse-gas emissions through the decomposition of organic materials in disposal sites, open burning and the fuel used for collection and transportation. The scale of emissions depends on waste composition, collection coverage, recycling, composting, landfill management and treatment technology. Global urban-system evidence demonstrates systematic scaling of waste generation with settlement size, while life-cycle and classification studies show that waste sorting and recovery pathways affect emissions from municipal waste systems (Lu et al., 2024; Li et al., 2024). Accordingly, a national waste-generation variable is relevant, but it should not be treated as a direct measure of waste-sector emissions without information on composition and disposal practices. The empirical relationship between Urbanization and environmental quality remains contested. African panel evidence indicates that financial development, renewable energy and Urbanization interact in shaping emissions, while research on sustainable Urbanization finds that institutional quality and digitalisation can reduce climate vulnerability (Kong et al., 2024; Yeyouomo & Asongu, 2024). Other studies identify spatial spillovers, nonlinear effects and different outcomes across pollutants, cities and income groups (Pickson et al., 2024; Liu et al., 2024a; Zhang et al., 2024; Yang et al., 2025; Khan et al., 2025). These differences caution against transferring findings from other countries directly to Nigeria. Against this background, this study examines the relationship between Urbanization and environmental degradation in Nigeria over 1990–2024. It focuses on urban population, population density, industrial output and waste generation, using CO_2 emissions as the proxy for environmental degradation. The study applies the STIRPAT perspective and an ARDL framework to distinguish short-run changes from long-run relationships. Its contribution lies in jointly examining four Urbanization-related variables within a Nigerian annual time-series model. Recent Nigerian evidence using ecological load-capacity measures also confirms the importance of investigating Urbanization alongside economic and resource-use factors, while broader West African research highlights the public-health implications of urban environmental practices (Akadiri et al., 2025; Ogwu et al., 2026). The analysis is limited to CO_2 emissions and should not be interpreted as covering every dimension of environmental degradation.

Statement of the Problem

Rapid Urbanization creates opportunities for employment, investment and access to services, but it can also intensify environmental pressures when the growth of

settlements exceeds the capacity of infrastructure and public institutions. In Nigeria, urban population growth is associated with increasing demand for transport, electricity, housing, water and waste services. Where these systems are inefficient, the environmental costs may include higher carbon emissions, poor air quality, land conversion and unmanaged solid waste. Although international research has examined Urbanization and carbon emissions, the estimated effects of urban population and density are not consistent across countries and development settings. For example, global city-level research identifies different contributions from urban extent, population density and per-capita emissions, while cross-country studies show that population density may have different effects across income groups (Luqman et al., 2023; Pickson et al., 2024; Yang et al., 2025). This inconsistency makes country-specific analysis necessary. A further gap concerns the joint examination of urban population, population density, industrial output and waste generation in Nigeria over a long annual period. The extent to which these variables are individually associated with CO_2 emissions is not adequately established by considering Urbanization as a single aggregate measure. This study addresses that empirical gap using annual data for 1990–2024. However, the interpretation of the results depends on transparent definitions and consistent measurement of population density, industrial output and waste generation.

Aim and Objectives of the Study

The broad aim of this study is to examine the relationship between Urbanization and environmental degradation in Nigeria from 1990 to 2024.

The specific objectives are to:

- examine the relationship between urban population and CO_2 emissions in Nigeria;
- analyse the relationship between population density and CO_2 emissions in Nigeria;
- assess the relationship between industrial output and CO_2 emissions in Nigeria; and
- investigate the relationship between waste generation and CO_2 emissions in Nigeria.

Research Questions

- What relationship exists between urban population and CO_2 emissions in Nigeria?
- How is population density related to CO_2 emissions in Nigeria?
- What is the relationship between industrial output and CO_2 emissions in Nigeria?
- To what extent is waste generation associated with CO_2 emissions in Nigeria?

Research Hypotheses

The following null hypotheses guide the empirical analysis:

- H_{01}: Urban population has no statistically significant relationship with CO_2 emissions in Nigeria.
- H_{02}: Population density has no statistically significant relationship with CO_2 emissions in Nigeria.
- H_{03}: Industrial output has no statistically significant relationship with CO_2 emissions in Nigeria.
- H_{04}: Waste generation has no statistically significant relationship with CO_2 emissions in Nigeria.

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Conceptual Review

Urbanization and Environmental Degradation

Urbanization refers to the increasing concentration of population and economic activities in urban settlements. Environmental degradation refers to the deterioration of environmental quality through pollution, ecosystem disturbance, resource depletion and greenhouse-gas emissions. This study operationalises environmental degradation using CO_2 emissions. This indicator is relevant to climate change but does not measure all environmental outcomes, including water pollution, biodiversity loss, local particulate pollution or soil degradation. The conclusions must therefore be confined to the emissions proxy used.

Urban Population and Population Density

Urban population captures the scale of the population living in urban areas, usually expressed as a number or percentage of the national population. Population density measures population relative to land area. Density can increase emissions through congestion, concentrated energy demand and pressure on public services, but it can also reduce emissions where compact development supports public transport and efficient infrastructure. Recent evidence indicates that the relationship is conditional on city form, income level and the scale of urban expansion (Luqman et al., 2023; Pickson et al., 2024; Yang et al., 2025).

Industrial Output

Industrial output represents the scale of production in the industrial sector. Industrial production can increase emissions through fuel combustion, process-related

releases and freight transport. However, the environmental impact depends on the industrial subsectors represented, energy efficiency, technology and environmental regulation. The precise indicator used in this study must be confirmed: industry value added as a percentage of GDP, an industrial production index and real industrial output are not interchangeable measures.

Waste Generation

Waste generation refers to the quantity of solid waste produced by households, commercial activities and other urban sources over a defined period. Waste-related emissions depend on organic content, disposal conditions, open burning, recycling, composting and treatment. Studies of municipal waste systems show that classification, source separation and recovery can alter the emissions profile of waste management (Li et al., 2024). The annual Nigerian series used in this study requires clear documentation of its source, geographical coverage, unit and estimation method.

Empirical Review

Luqman et al. (2023) analyzed urban CO_2 emissions in 91 cities using a globally consistent time-resolved dataset. They decomposed emissions trends into urban extent, population density and per-capita emissions and found that the dominant contributors differed according to development level. Their findings show why the environmental effect of Urbanization should not be attributed to population growth alone.

Wojewodzki et al. (2023) examined the convergence of carbon emissions across countries with different Urbanization and agricultural structures. Their results identified multiple convergence clubs and showed that emissions trajectories vary across national groups. The study reinforces the importance of structural and contextual factors when interpreting aggregate Urbanization-emissions relationships. Pickson et al. (2024) investigated population-related determinants of CO_2 emissions across country income groups. They reported a positive Urbanization-emissions relationship across income groups, while the influence of population density differed by income category. This finding is relevant to Nigeria because it suggests that population concentration may not have a uniform environmental effect across national contexts.

Quan et al. (2024) applied the STIRPAT framework to investigate Urbanization, economic growth and energy sustainability in OECD countries. Their analysis highlights the importance of energy-related variables in explaining environmental pressure and demonstrates the continued relevance of the STIRPAT approach. Although their sample differs from Nigeria, the study provides a theoretical and methodological basis for examining population and production-related factors jointly. Li et al. (2024) assessed carbon emissions from municipal solid waste under alternative classification methods in Yunnan Province, China. Their study demonstrated that waste sorting and recovery scenarios can influence emissions from municipal waste systems. Liu et al. (2024) similarly examined the carbon-emissions implications of a municipal solid-waste classification policy in Beijing, illustrating the potential environmental significance of waste-management arrangements. Lohwasser et al. (2025) used a regional STIRPAT approach to examine population, affluence and Urbanization in German districts. They found that environmental effects varied across settlement structures and that the influence of industrial manufacturing and urban density depended on regional characteristics. This result is relevant to interpreting the insignificant industrial-output coefficient in the present study: aggregate measures may conceal sectoral and spatial variation.

Yang et al. (2025) analyzed global urban expansion and CO_2 emissions using remote-sensing and geographic information systems data. They found heterogeneous relationships among population density, physical compactness, land area and emissions. Their results caution against assuming that higher density necessarily increases emissions in every setting. Laziou and Lemoy (2025) examined the three-dimensional structure of population density in world cities and demonstrated that density patterns vary within and across urban areas. Their work underscores the importance of distinguishing national population density from urban density and from intra-urban density when operationalizing demographic variables.

Zhang et al. (2025) investigated the measurement of Urbanization and its spatially heterogeneous effects on carbon emissions in the district-heating industry in China. Their results indicate that the environmental consequences of Urbanization vary across places and sectors, supporting the need for context-sensitive interpretation rather than a single universal coefficient.

Recent Africa-focused evidence is particularly relevant to the interpretation of national Urbanization indicators. Liu et al. (2024a) reviewed city-level greenhouse-gas inventories across 54 African countries and identified substantial gaps in coverage and comparability. Their findings reinforce the need to interpret Nigeria's national time-series estimates cautiously: national aggregates may conceal city-level differences, and the absence of standardized local inventories limits the ability to identify the precise urban sources of emissions.

Studies published in 2024–2026 also show why the Urbanization–environment relationship should not be assumed to be linear or uniformly harmful. Kong et al. (2024) found that the effects of Urbanization and related

economic variables on emissions in African economies need to be assessed alongside renewable energy and financial development. Yeyouomo and Asongu (2024) reported that sustainable Urbanization can reduce climate vulnerability through digitalization and institutional quality. In a Nigerian application, Akadiri et al. (2025) found that Urbanization was associated with lower environmental load capacity in the long run, using an asymmetric quantile approach. These studies suggest that institutional capacity, energy structure and the selected environmental indicator can alter the estimated relationship.

Spatial and transport studies further explain why aggregate population measures may produce different coefficient signs. Liu et al. (2024b) reported nonlinear direct and spatial spillover effects of urban expansion on carbon emissions, with industrial structure and agglomeration among the transmission mechanisms. Zhang et al. (2024) showed that Urbanization can affect carbon-emission performance through spatially differentiated pathways. Lyu et al. (2025) found that urban sprawl can raise emissions while more efficient public transport can moderate this effect. Wen et al. (2024) similarly linked sprawl with lower carbon-emission efficiency. These findings support the distinction between urban population size and population density adopted in the present study. Recent 2026 evidence also identifies nonlinear and interactive effects of urban fragmentation on carbon emissions (Yu et al., 2026).

Waste and urban-service research provides a complementary explanation for including waste generation. Lu et al. (2024) documented scaling relationships between urban-system size and waste generation, indicating that waste pressure is not independent of settlement structure. Li et al. (2024) showed that municipal-waste classification methods affect estimated emissions, underscoring the importance of composition and treatment pathways. For Nigeria and West Africa, Ogwu et al. (2026) connect urban environmental practices with public health and the provision of basic services. These findings strengthen the policy relevance of waste governance, but they also show that waste tonnage alone cannot identify methane generation, open-burning emissions or the performance of collection and disposal systems.

The latest urban sustainability literature also emphasizes context-specific measurement and the integration of environmental, social and institutional dimensions. Afinowi and Monkam (2025) argue that standardised urban indicators often overlook informality, inequality and governance constraints in African cities. Almulhim and Cobbinah (2026) similarly frame urban sustainability as a response to the interacting pressures of Urbanization and climate change, while Chimhowu et al. (2026) identify weak coordination, service-delivery gaps and limited monitoring as persistent barriers to achieving the Sustainable Development Goals in African cities. These studies support the present paper's emphasis on transparent data definitions and locally appropriate policy recommendations.

Theoretical Framework: STIRPAT

This study is anchored on the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) framework. STIRPAT is an empirical extension of the IPAT identity, which conceptualizes environmental impact (I) as a function of population (P), affluence (A) and technology (T). Unlike the deterministic IPAT identity, STIRPAT permits the elasticities of the explanatory factors to be estimated and allows additional variables to be incorporated. The general STIRPAT specification is expressed as:

$$I_t = aP_t^b A_t^c T_t^d e_t.$$

Taking natural logarithms gives:

$$\ln I_t = \alpha + \beta \ln P_t + \gamma \ln A_t + \delta \ln T_t + \varepsilon_t.$$

In this study, CO_2 emissions represent environmental impact; urban population and population density represent demographic dimensions; industrial output represents the production/affluence dimension; and waste generation captures an additional pressure associated with urban consumption and production. The expected direction of the coefficients is generally positive where demographic and economic growth increase fossil-energy use, transport demand, production and waste disposal. However, the empirical effects may differ according to energy sources, technology, urban form, waste treatment and environmental regulation. Recent applications of STIRPAT demonstrate that population, affluence and Urbanization effects are context-dependent (Quan et al., 2024; Lohwasser et al., 2025).

METHODOLOGY

Research Design

The study adopted an ex-post facto research design because it examines historical macroeconomic and environmental variables that cannot be manipulated by the researcher. Annual observations were used to estimate the relationships among CO_2 emissions, urban population, population density, industrial output and waste generation. Since the design is observational, the estimated coefficients should be interpreted as conditional statistical relationships rather than definitive causal effects.

Nature and Sources of Data

The study used annual secondary time-series data for Nigeria covering 1990–2024, giving 35 annual observations before the loss of observations associated with differencing and lag selection. The submitted manuscript identifies the Central Bank of Nigeria (CBN), the National Bureau of Statistics (NBS) and the World Bank's World Development Indicators (WDI) as data sources. The authors should provide the exact series title, indicator code, unit, download date and any interpolation or estimation procedure for each variable. In particular, the source and construction of the annual waste-generation series must be made explicit. The original manuscript describes population density as persons per square kilometre in urban areas, industrial output as the contribution of industry to GDP or output, and waste generation as municipal waste in urban areas. These definitions are not sufficiently precise to establish the exact statistical series. The authors must verify whether population density is national or urban density, whether industrial output is an index or a share of GDP, and whether the waste series is total national or municipal waste. These details are essential for reproducibility and interpretation.

Model Specification

The functional relationship is specified as:

$$\mathbf{CO_{2t} = f(URB_t, POPD_t, INDO_t, WASG_t)}$$

The corresponding linear empirical relationship is:

$$CO_{2t} = \beta_0 + \beta_1 URB_t + \beta_2 POPD_t + \beta_3 INDO_t + \beta_4 WASG_t + \varepsilon_t$$

Where CO_2 represents carbon dioxide emissions; URB is urban population; POPD is population density; INDO is industrial output; WASG is waste generation; β_0 is the intercept; β_1–β_4 are parameters to be estimated; and ε is the stochastic error term. The original output does not clearly establish whether the variables were logged before estimation. The authors must confirm this from the EViews workfile/output. If logged variables were used, the model equation and coefficient interpretation should be presented in log-linear form.

The a priori expectation is β_1, β_2, β_3 and $\beta_4 > 0$, based on the expectation that urban population growth, population concentration, industrial activity and waste generation may increase emissions. This is a theoretical expectation and does not predetermine the estimated signs.

Estimation Technique

The study employed the autoregressive distributed lag (ARDL) bounds-testing approach. This approach is suitable for a single-equation time-series model containing a mixture of I(0) and I(1) variables, provided that none of the series is integrated of order two, I(2). The procedure estimates short-run dynamics and tests for a long-run levels relationship within a unified framework. The analysis involved descriptive statistics, Augmented Dickey–Fuller (ADF) unit-root tests, ARDL bounds testing, estimation of long-run coefficients and the error-correction representation. The bounds-test F-statistic was compared with the lower I(0) and upper I(1) critical bounds. A statistic above the upper bound indicates evidence of a long-run relationship; a statistic below the lower bound indicates no such evidence; and a statistic between the bounds is inconclusive. The error-correction coefficient is expected to be negative and statistically significant where the system adjusts towards long-run equilibrium. Its absolute value indicates the proportion of the previous period's disequilibrium corrected in one period. The supplied manuscript reports descriptive fit statistics and a Durbin–Watson statistic, but does not provide a complete set of formal diagnostic tests. The final submission should include serial-correlation, heteroskedasticity, functional-form and parameter-stability tests if these were conducted.

RESULTS AND DISCUSSION

This section retains the five statistical tables from the submitted manuscript. The tables have been renumbered consecutively from (Table 1), with their values preserved. The narrative has been corrected to agree with the displayed coefficients and probability values. No estimates have been recalculated.

Descriptive Statistics

Table 1 presents the distributional characteristics of the five variables over the study period. CO_2 emissions have a mean of 14,337.14 and a standard deviation of 4,823.599, indicating substantial variation around the sample average. The minimum and maximum values of 6,800 and 22,300 kilotonnes respectively show that emissions changed considerably during the period. This variation provides a basis for examining whether demographic, industrial and waste-related factors are associated with changes in emissions. Urban population has a mean of 41.36%, with values ranging from 29.68% to 55.03%. The standard deviation of 8.05 indicates variation in the urban share of the population across the annual observations. Population density has a mean of 151.60 persons per square kilometre and ranges from 103 to 208. The standard deviation of 31.99 indicates that the density series also varies over time. These statistics describe the national series as supplied; they do not establish whether the density measure is specifically urban density. Industrial output has a mean of 29.09 and ranges

Table 1. Descriptive statistics of the study variables, 1990–2024

Statistic	CO_2 emissions	Urban population (URB)	Population density (POPD)	Industrial output (INDO)	Waste generation (WASG)
Mean	14,337.14	41.36171	151.6000	29.09171	64.48571
Median	14,400.00	40.82000	149.0000	28.57000	66.00000
Maximum	22,300.00	55.03000	208.0000	38.08000	110.0000
Minimum	6,800.000	29.68000	103.0000	18.37000	21.00000
Standard deviation	4,823.599	8.049615	31.99283	5.206026	26.68815
Skewness	0.027713	0.162321	0.162551	0.059529	−0.006650
Kurtosis	1.754979	1.686935	1.793669	2.212623	1.779249
Jarque–Bera	2.265010	2.668067	2.276349	0.924783	2.173515
Probability	0.322225	0.263413	0.320403	0.629776	0.337308

Table 2. Augmented Dickey–Fuller unit-root test results

Variable	At level: ADF statistic (p-value)	First difference: ADF statistic (p-value)	Second difference: ADF statistic (p-value)	Order of integration
CO_2 emissions	−5.5055 (0.0001)	−2.6769 (0.0887)	−5.9951 (0.0000)	I(0)
Urban population (URB)	−1.5149 (0.5137)	−3.6920 (0.0123)	−1.6516 (0.4399)	I(1)
Population density (POPD)	−2.4721 (0.1309)	−4.5684 (0.0009)	−6.2339 (0.0000)	I(1)
Industrial output (INDO)	−1.9140 (0.3222)	−5.8439 (0.0000)	−8.0769 (0.0000)	I(1)
Waste generation (WASG)	−10.3470 (0.0000)	−2.3954 (0.1509)	−5.0558 (0.0003)	I(0)

Table 3. ARDL bounds test for a long-run relationship

Test statistic / significance	Lower bound, I(0)	Upper bound, I(1)
F-statistic	10.58627	4
10% critical bounds	2.45 (I(0))	3.52 (I(1))
5% critical bounds	2.86 (I(0))	4.01 (I(1))
1% critical bounds	3.74 (I(0))	5.06 (I(1))

from 18.37 to 38.08. Because the original manuscript does not identify the precise unit or indicator code, the values should not be interpreted as a percentage or index until the source series is confirmed. Waste generation has a mean of 64.49, with a minimum of 21 and a maximum of 110. The original narrative describes these values as million tonnes, but the geographical coverage and estimation method of the annual series must be documented. The Jarque–Bera probability values for all five series exceed 0.05. Accordingly, normality is not rejected for the individual series at the 5% level. This finding concerns the marginal distribution of each variable and does not establish that the regression residuals are normally distributed. Residual diagnostics should be reported separately.

Unit-Root Test

Table 2 reports the ADF unit-root test results. CO_2 emissions are stationary at level, with an ADF statistic of −5.5055 and a probability value of 0.0001. Waste generation is also stationary at level (ADF = −10.3470; $p < 0.001$). These results indicate that the two variables are integrated of order zero, I(0). Urban population is non-stationary at level ($p = 0.5137$) but becomes stationary after first differencing (ADF = −3.6920; $p = 0.0123$), indicating I(1). Population density similarly becomes stationary after first differencing (ADF = −4.5684; $p = 0.0009$), while industrial output is also stationary at first difference (ADF = −5.8439; $p < 0.001$). Thus, the reported series contain a mixture of I(0) and I(1) variables. The mixed order of integration supports the use of the ARDL bounds-testing approach, provided that none of the variables is I(2). The second-difference statistics are retained in Table 2 for transparency, but the classification is based on the first level at which stationarity is achieved. The authors should verify the ADF specification, including intercept/trend terms and lag selection, because these choices affect unit-root results.

ARDL Bounds Test

Table 3 presents the ARDL bounds test. The calculated F-statistic is 10.58627, which is higher than the reported upper-bound critical value of 4.01 at the 5% significance level. It also exceeds the reported upper bounds at the 10% and 1% levels (3.52 and 5.06 respectively). On the basis of the critical values supplied, the null hypothesis of no long-run relationship is rejected. The result provides evidence of a long-run levels relationship among CO_2 emissions, urban population, population density, industrial output and waste generation. The bounds-test decision is conditional on the validity of the selected ARDL specification and the critical values used. The authors

Table 4: Long-run ARDL estimates

Variable	Coefficient	Standard error	t-statistic	Probability
Urban population (URB)	−0.380512	0.489064	−0.778041	0.4461
Population density (POPD)	1.170296	0.527760	2.217475	0.0390
Industrial output (INDO)	−0.017187	0.019051	−0.902156	0.3783
Waste generation (WASG)	0.357932	0.064769	5.526307	0.0000
Constant (C)	3.662451	0.598455	6.119845	0.0000

Note: Statistical significance is assessed at the 5% level. Source: Researchers' computation using EViews 9.0,

Table 5. Short-run ARDL and error-correction estimates

Variable	Coefficient	Standard error	t-statistic	Probability
ΔCO_2 emissions (−1)	0.377551	0.179045	2.108697	0.0485
ΔCO_2 emissions (−2)	0.357717	0.176753	2.023826	0.0573
Δ Urban population	1.547329	1.025490	1.508869	0.1478
Δ Population density	0.622166	0.460552	1.350914	0.1926
Δ Population density (−1)	0.566724	0.455846	1.243236	0.2289
Δ Industrial output	−0.014378	0.014294	−1.005874	0.3271
Δ Waste generation	−0.341644	0.161912	−2.110059	0.0483
Δ Waste generation (−1)	−0.462646	0.158762	−2.914080	0.0089
Error-correction term [CointEq(−1)]	−0.836582	0.196562	−4.256072	0.0004

Note: Δ denotes first difference; (−1) and (−2) denote one- and two-period lags. Source: Researchers' computation using EViews 9.0,

should confirm the deterministic case, lag order and finite-sample critical-value source in the original EViews output. This is especially important because the sample contains 35 annual observations.

Long-Run Estimates

Table 4 reports the estimated long-run coefficients. The coefficient of urban population is negative (−0.380512), but the probability value of 0.4461 exceeds 0.05. Therefore, the study does not find a statistically significant long-run relationship between urban population and CO_2 emissions after controlling for the other variables. The negative sign should not be interpreted as evidence that Urbanization reduces emissions because the estimate is statistically insignificant.

Population density has a positive coefficient of 1.170296 and is statistically significant at the 5% level (p = 0.0390). This indicates that higher population density is positively associated with CO_2 emissions in the long run, conditional on the other regressors. The result may be consistent with concentrated demand for transport, energy and urban services, although the model does not directly test these mechanisms. The result should be interpreted in light of evidence that the effect of density depends on city form, transport provision and infrastructure quality (Luqman et al., 2023; Yang et al., 2025; Lyu et al., 2025). Industrial output has a negative coefficient of −0.017187, but the probability value of 0.3783 indicates that the relationship is statistically insignificant. The result does not establish that industrial activity is environmentally harmless. Rather, the aggregate indicator used in the model does not show a statistically distinguishable long-run relationship in this specification. Differences among industrial subsectors, energy efficiency and environmental regulation may be obscured by an aggregate measure. Waste generation has a positive coefficient of 0.357932 and is statistically significant (p < 0.001). This suggests a positive long-run association between waste generation and CO_2 emissions. The finding is consistent with the broader evidence that waste composition, classification and disposal practices can influence emissions from municipal waste systems (Li et al., 2024). The interpretation nevertheless depends on confirming the construction and unit of the Nigerian waste-generation series. Urban-system research confirms that waste generation scales with settlement size, while emissions depend on classification and treatment choices (Lu et al., 2024; Li et al., 2024). The constant term is positive and statistically significant (3.662451; p < 0.001). Its substantive interpretation depends on whether the model was estimated in levels or logarithms and on the scaling of the variables. It should therefore be reported as the intercept rather than described as an independent environmental mechanism.

Short-Run Estimates and Error-Correction Mechanism

Table 5 presents the short-run dynamics. The first lag of the dependent variable has a positive and statistically significant coefficient (0.377551; p = 0.0485), while the second lag is positive but not significant at the 5% level (p = 0.0573). This indicates some persistence in changes in CO_2 emissions, although the second lag does not meet the conventional 5% threshold. The contemporaneous change in urban population has a positive coefficient (1.547329), but it is statistically insignificant (p = 0.1478). The current and lagged changes in population density are also statistically insignificant (p = 0.1926 and p = 0.2289 respectively). The change in industrial output is negative and statistically insignificant (p = 0.3271). Accordingly, the displayed short-run estimates do not support claims that

urban population, population density or industrial output has a statistically significant short-run effect at the 5% level. By contrast, the current change in waste generation has a negative and statistically significant coefficient (−0.341644; p = 0.0483), while its one-period lag is also negative and significant (−0.462646; p = 0.0089). These short-run signs differ from the positive long-run coefficient in Table 4. The result indicates that the short-run association is not consistent in sign with the long-run relationship. The difference may reflect dynamic adjustment, the lag structure or the measurement properties of the waste series; it should not be explained as a confirmed behavioural mechanism without further analysis. The error-correction coefficient is negative (−0.836582) and statistically significant (p = 0.0004). This supports adjustment towards the estimated long-run relationship. Its magnitude indicates that approximately 83.66% of the preceding period's disequilibrium is corrected within one year, given annual observations and the reported model specification. The speed of adjustment is relatively high and implies that deviations from the long-run relationship are substantially reduced within the following period.

Model Fit and Diagnostic Information

The submitted manuscript reports an R-squared value of 0.9198, an adjusted R-squared of 0.9096 and a Durbin–Watson statistic of 2.0496. The R-squared indicates that approximately 91.98% of the in-sample variation in the dependent variable is accounted for by the estimated model, while the adjusted R-squared is 0.9096 after adjustment for the number of regressors. The Durbin–Watson statistic is close to 2, which does not suggest strong first-order residual autocorrelation on its own. However, the Durbin–Watson statistic is not a substitute for a formal Breusch–Godfrey serial-correlation LM test. The original manuscript does not provide complete test statistics for heteroskedasticity, functional form or parameter stability; these should be added only if supported by the EViews output. A high R-squared should not be treated as proof of model validity.

DISCUSSION

The positive and significant long-run relationship between population density and CO_2 emissions suggests that population concentration is an important correlate of emissions in the Nigerian model. This finding is consistent with research showing that demographic factors and urban form are relevant to emissions, although the direction and magnitude of density effects vary across income groups and cities (Pickson et al., 2024; Luqman et al., 2023; Yang et al., 2025). It also highlights the need to clarify whether the density series measures national or specifically urban density. Recent studies also show that density and compactness can have different emissions effects and that urban expansion can create spatial spillovers (Liu et al., 2024b; Yang et al., 2025; Zhang et al., 2024). The negative but insignificant coefficient for urban population indicates that the urban share of the population does not independently explain long-run CO_2 emissions in this specification once the other variables are controlled for. This differs from cross-country findings reporting a positive Urbanization-emissions association (Pickson et al., 2024), but such differences may arise from sample composition, measurement, energy structure, spatial scale and model specification. Global city-level evidence also shows that urban extent, density and per-capita emissions can make different contributions to overall emissions trends (Luqman et al., 2023). This is consistent with African evidence that Urbanization does not have a single, context-independent effect and that renewable energy, institutions and digitalisation can condition the relationship (Kong et al., 2024; Yeyouomo & Asongu, 2024).

The insignificant industrial-output coefficient suggests that the aggregate industrial indicator used in the model does not have a statistically significant long-run association with CO_2 emissions. This should not be interpreted as evidence that industrial activity has no environmental consequences. Research using regional STIRPAT models finds that the relationship between industrial manufacturing, density and environmental outcomes can depend on regional structure (Lohwasser et al., 2025). Future research could disaggregate manufacturing, mining, construction and oil-and-gas activities. The result is also consistent with the argument that industrial structure and agglomeration, rather than aggregate industrial output alone, may be the relevant transmission channels (Liu et al., 2024b; Ma et al., 2024).

The positive long-run relationship between waste generation and CO_2 emissions supports the importance of waste-management policy. Research on municipal waste emissions demonstrates that waste classification, sorting and recovery options influence the emissions profile of waste systems (Li et al., 2024). However, the negative short-run waste coefficients in Table 5 require careful interpretation. It is possible that the short-run estimates reflect transitional effects or data/lag characteristics, but these explanations require validation using the original series and alternative specifications. Recent evidence further indicates that urban-system size, waste composition and treatment methods are central to interpreting waste-related environmental impacts (Lu et al., 2024; Li et al., 2024).

The findings identify population density and waste generation as the statistically significant positive long-run correlates among the explanatory variables included in the model. Urban population and industrial output are not statistically significant in the long run, while short-run

waste-generation coefficients are negative and significant. These distinctions are important because the original manuscript overstated the significance of urban population and described the waste-generation relationship as consistently positive across both horizons.

IMPLICATIONS OF THE RESULTS

Implications for Society and Public Policy

First, the positive long-run association between population density and CO_2 emissions indicates the importance of integrated urban planning. Federal, state and local authorities should coordinate housing, land use, transport, electricity, sanitation, drainage and green-space development. Urban density should be supported by reliable public transport, walkable neighbourhoods and efficient infrastructure so that population concentration does not automatically translate into higher emissions. This recommendation is consistent with evidence that the carbon consequences of sprawl depend partly on public-transport efficiency and urban form (Lyu et al., 2025; Wen et al., 2024).

Second, the positive long-run relationship between waste generation and CO_2 emissions supports investment in integrated municipal solid-waste management. Policy priorities should include regular collection, source separation, recycling, composting of suitable organic waste, controlled landfill management and prevention of open burning and indiscriminate dumping. Waste-to-energy options should be assessed using technical, economic and environmental criteria rather than assumed to be appropriate in every locality. The emphasis on source separation and recovery is supported by recent evidence that municipal-waste classification and treatment pathways affect emissions (Li et al., 2024; Lu et al., 2024). Third, the insignificant industrial-output coefficient should not lead policymakers to relax industrial environmental regulation. The aggregate indicator may not capture differences between industrial subsectors or emissions intensity. Regulators should continue to monitor industrial emissions, promote cleaner production, improve energy efficiency and enforce environmental standards, particularly in energy-intensive sectors. Finally, urban environmental policy has implications for households and businesses through public health, service reliability, neighbourhood quality and the long-term cost of infrastructure. Environmental management should therefore combine emissions reduction with affordable urban services, local employment and protection of vulnerable communities.

Implications for the Research Community

The study contributes a Nigerian annual time-series analysis covering 1990–2024 and examines four Urbanization-related variables jointly. It also demonstrates the value of distinguishing short-run dynamics from long-run relationships. The different signs of the short-run and long-run waste-generation coefficients provide a specific empirical issue for further investigation. Future studies should improve data transparency by reporting the exact WDI indicator codes, CBN and NBS series titles, units, geographical coverage, source years and missing-data treatment. Particular attention should be given to the annual waste-generation series, including whether values are observed or modelled estimates. Researchers should also distinguish national population density from urban and intra-urban density. The need for context-specific, comparable urban indicators is also emphasised in recent African urban-sustainability research (Liu et al., 2024a; Afinowi & Monkam, 2025; Chimhowu et al., 2026). Further work could use alternative environmental indicators, including methane emissions, ecological footprint, particulate matter, land-use change and waste-sector greenhouse-gas emissions. Robustness checks should include alternative lag-selection criteria, structural-break tests, alternative unit-root procedures and sensitivity analyses using different measures of industrial activity and waste generation.

CONCLUSION

This study examined the relationship between Urbanization and environmental degradation in Nigeria over 1990–2024, using CO_2 emissions as a proxy for environmental degradation and urban population, population density, industrial output and waste generation as explanatory variables. The reported ADF results indicate a mixture of I(0) and I(1) variables, while the ARDL bounds statistic exceeds the reported upper critical bound, supporting a long-run relationship among the variables. The long-run estimates show that population density and waste generation are positively and statistically significantly associated with CO_2 emissions. Urban population and industrial output are statistically insignificant in the long run. In the short run, current and lagged changes in waste generation have negative and statistically significant coefficients, while changes in urban population, population density and industrial output are not significant at the 5% level. The negative and significant error-correction coefficient indicates adjustment towards the long-run relationship.The study concludes that population density and waste generation are the principal positive long-run correlates of CO_2 emissions among the variables considered. Sustainable urban development in Nigeria requires integrated spatial planning, efficient public infrastructure, effective waste governance and continued industrial environmental oversight. These conclusions are conditional on the accuracy and consistency of the

underlying annual series and should not be interpreted as definitive causal effects.

RECOMMENDATIONS

(a) Government at federal, state and local levels should strengthen integrated urban and regional planning so that housing, transport, sanitation, drainage, energy and green infrastructure develop in line with population concentration.

(b) Local governments should improve municipal waste collection and disposal, promote source separation and recycling, expand composting where suitable, and prevent open burning and uncontrolled dumping.

(c) Environmental regulators should maintain industrial emissions monitoring and promote cleaner production, energy efficiency and compliance with environmental standards, regardless of the insignificant aggregate industrial-output coefficient in this study.

(d) Relevant statistical agencies should improve the availability of consistent annual municipal solid-waste data and publish clear definitions, units, geographical coverage and estimation methods.

(e) Future researchers should test the robustness of these findings using alternative emissions indicators, structural-break procedures, clearly defined urban-density measures and disaggregated industrial-sector data.

REFERENCES

Afinowi, T., & Monkam, N. (2025). Advancing context-specific urban indicators for African cities: A systematic review. npj Urban Sustainability, 5, Article 105. https://doi.org/10.1038/s42949-025-00292-y

Akadiri, S. S., Ozkan, O., & Alola, A. A. (2025). Investigating the determinants of load capacity factor in Nigeria: An asymmetric quantile approach on urbanization, economic growth, FDI, and resource dependency. Resources Policy, 104, 105586. https://doi.org/10.1016/j.resourpol.2025.105586

Almulhim, A. I., & Cobbinah, P. B. (2026). On urban sustainability: Urbanization and climate change collision. Sustainable Development, 34(S2), 979–995. https://doi.org/10.1002/sd.70382

Chimhowu, A., Langnel, Z., Mensah, J. K., Agyabeng, A. N., & Bawole, J. N. (2026). Attaining Sustainable Development Goals in African cities: A systematic literature review. Sustainable Development, 1–17. https://doi.org/10.1002/sd.71086

Khan, S., Zhang, L., Yuan, H., & Hussain, M. (2025). Policy pathways to carbon neutrality: The role of urbanization and ICT in achieving SDG-13 through linear and nonlinear dynamics. Journal of Cleaner Production, 522, 146295. https://doi.org/10.1016/j.jclepro.2025.146295

Kong, Y., Donkor, M., Jin, C., Musah, M., & Nkyi, J. A. (2024). Do financial development, urbanization, economic growth and renewable energy promote the emission mitigation agenda of Africa? Evidence from models that account for cross-sectional dependence and slope heterogeneity. Frontiers in Environmental Science, 11, 1269416. https://doi.org/10.3389/fenvs.2023.1269416

Laziou, G., & Lemoy, R. (2025). The three-dimensional structure of population density in world cities. npj Urban Sustainability, 5, Article 75. https://doi.org/10.1038/s42949-025-00262-4

Li, B., Li, D., Hu, J., Zhu, X., Wang, H., Jeon, C.-h., Kim, G.-M., & Zeng, Y. (2024). Carbon emission of municipal solid waste under different classification methods in the context of carbon neutrality: A case study of Yunnan Province, China. Fuel, 372, 132167. https://doi.org/10.1016/j.fuel.2024.132167

Liu, B., Shan, Y., Kuik, R., Ji, X., Chapungu, L., Yang, X., & Hubacek, K. (2024a). The landscape of city-level GHG emission accounts in Africa. Journal of Industrial Ecology, 28(6), 1377–1391. https://doi.org/10.1111/jiec.13562

Liu, X., Xu, H., & Zhang, M. (2024b). The effects of urban expansion on carbon emissions: Based on the spatial interaction and transmission mechanism. Journal of Cleaner Production, 434, 140019. https://doi.org/10.1016/j.jclepro.2023.140019

Lohwasser, J., Bolognesi, T., & Schaffer, A. (2025). Impacts of population, affluence and urbanization on local air pollution and land transformation: A regional STIRPAT analysis for German districts. Ecological Economics, 227, 108416. https://doi.org/10.1016/j.ecolecon.2024.108416

Lu, M., Zhou, C., Wang, C., Jackson, R. B., et al. (2024). Worldwide scaling of waste generation in urban systems. Nature Cities, 1, 126–135. https://doi.org/10.1038/s44284-023-00021-5

Luqman, M., Rayner, P. J., & Gurney, K. R. (2023). On the impact of Urbanization on CO_2 emissions. npj Urban Sustainability, 3, Article 6. https://doi.org/10.1038/s42949-023-00084-2

Lyu, S., Huang, Y., & Sun, T. (2025). Urban sprawl, public transportation efficiency and carbon emissions. Journal of Cleaner Production, 144652. https://doi.org/10.1016/j.jclepro.2025.144652

Ma, D., Yan, Y., Xiao, Y., Zhang, F., Zha, H., Chang, R., Zhang, J., Guo, Z., & An, B. (2024). Research on the spatiotemporal evolution and influencing factors of urbanization and carbon emission efficiency coupling coordination: From the perspective of global countries. Journal of Environmental Management, 360, 121153. https://doi.org/10.1016/j.jenvman.2024.121153

Ogwu, S. O., Onwe, J. C., Celik, B. A., & Ezemenahi, S. I. (2026). Urbanization and environmental practices on public health: Sustainable solutions to Sustainable Development Goals 3, 6, and 11 in rapidly urbanizing developing countries in West Africa. Sustainable Development, 1–13. https://doi.org/10.1002/sd.70714

Pickson, R. B., Gui, P., Jian, L., & Boateng, E. (2024). Do population-related factors matter for carbon emissions? Lessons from different income groups of countries. Urban Climate, 55, 101934. https://doi.org/10.1016/j.uclim.2024.101934

Quan, Z., Xu, X., Jiang, J., Wang, W., & Gao, S. (2024). Uncovering the drivers of ecological footprints: A STIRPAT analysis of urbanization, economic growth, and energy sustainability in OECD countries. Journal of Cleaner Production, 475, 143686. https://doi.org/10.1016/j.jclepro.2024.143686

Wen, H., Yu, H., & Nghiem, X.-H. (2024). Impact of urban sprawl on carbon emission efficiency: Evidence from China. Urban Climate, 55, 101986. https://doi.org/10.1016/j.uclim.2024.101986

Wojewodzki, M., Wei, Y., Cheong, T. S., & Shi, X. (2023). Urbanization, agriculture and convergence of carbon emissions nexus: Global distribution dynamics analysis. Journal of Cleaner Production, 385, 135697. https://doi.org/10.1016/j.jclepro.2022.135697

Yang, Z., Wu, J., Shang, X., Fu, R., Xie, L., & Ge, Q. (2025). Scaling laws of CO_2 emissions during global urban expansion. npj Urban Sustainability, 5, Article 3. https://doi.org/10.1038/s42949-024-00172-x

Yeyouomo, A. K., & Asongu, S. A. (2024). Sustainable urbanization and vulnerability to climate change in Africa: Accounting for digitalization and institutional quality. Sustainable Development, 32(1), 1188–1216. https://doi.org/10.1002/sd.2721

Yu, P., Deng, X., Chen, Y., & Li, Z. (2026). Unravelling nonlinear and interactive effects of urban fragmentation on carbon emissions in transitioning metropolitan areas. Journal of Cleaner Production, 552, 147976. https://doi.org/10.1016/j.jclepro.2026.147976

Zhang, W., Xu, Y., Streets, D. G., & Wang, C. (2025). Measurement of urbanization and its spatiotemporal heterogeneous effects on carbon emission from district heating industry in China. Energy and Buildings, 328, 115182. https://doi.org/10.1016/j.enbuild.2024.115182

Zhang, J., Yang, Y., Huang, J., & Kao, X. (2024). Can urbanization improve carbon performance? Frontiers in Environmental Science, 12, 1431324. https://doi.org/10.3389/fenvs.2024.1431324