



Technological Innovation and Urbanization as Drivers of Environmental Sustainability in Nigeria

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Abstract

This study analyzed the intricate relationship between technology, urbanization, economic growth, and environmental sustainability in Nigeria from 1990 to 2024. Utilizing the Environmental Kuznets Curve (EKC) framework and Dynamic Ordinary Least Squares (DOLS) methodology, it reveals that all variables were integrated of order one, indicating a stable long-run relationship. Key findings highlight a positive yet statistically insignificant impact of technology on environmental sustainability, hindered by weak institutional support and limited green innovation. Urbanization positively correlates with environmental outcomes when urban development is structured. Economic growth initially harms environmental sustainability at lower income levels but aligns with the EKC hypothesis, suggesting eventual improvement at higher income levels. Energy consumption and industrial value added have positive but insignificant effects on the environment. Notably, the interaction between technology and urbanization is negative and significant, implying that their concurrent growth exacerbates environmental issues due to inefficiencies. The study concludes that Nigeria's environmental sustainability is influenced by complex macroeconomic interactions and advocates for enhanced green policies, improved urban planning, cleaner energy transitions, structural transformations, and coordinated policy integration for sustainable outcomes. It recommended stronger green innovation policies, improved urban planning, cleaner energy transitions, structural transformation, and coordinated policy integration between technology and urban development to achieve sustainable environmental outcomes.

Keywords: Environmental Sustainability, Technological Innovation, Urbanisation, Sustainable Development, Nigeria

Introduction

Sustainable development poses a significant challenge for nations balancing economic growth, technological advancement, and environmental stewardship, particularly in Nigeria. As Africa's largest economy and most populous nation, Nigeria experiences rapid urbanization and increased technological adoption amidst environmental pressures (Aderinto, 2023; Okafor & Nworie, 2025). Projections suggest that approximately 60% of Nigeria's population may reside in urban areas by 2030, underscoring the urgent need for infrastructure and public services to keep pace with rapid urban growth and increasing demand (World Bank, 2016; Fox et al., 2018). The relationship between technology and urbanization in environmental sustainability is complex. Technological advancements can enhance resource efficiency and promote cleaner production, yet uncoordinated urban expansion often leads to environmental degradation through higher energy demand and waste generation (Obilor et al., 2024). The Endogenous Growth Theory (EGT) provides a framework to understand these dynamics, suggesting that technological innovation and human capital accumulation drive internal economic growth while potentially fostering sustainability through enhanced resource management. Despite ongoing reforms, Nigeria's economic growth remains below aspirations, with an estimated 3.4% growth in 2024 against a target of 6%. This underscores structural constraints in achieving growth while ensuring environmental integrity. Recent policy initiatives aim to bolster digital infrastructure and address the digital divide, contributing to a rise in internet penetration. The Nigeria Energy Transition Plan (ETP) establishes a pathway towards achieving net-zero emissions by 2060 while simultaneously addressing energy poverty and supporting economic development. The plan provides a framework for reducing emissions across five key sectors—

power, cooking, transport, industry, and oil and gas—thereby integrating climate action and environmental sustainability into Nigeria’s broader development strategy (Federal Government of Nigeria, 2022).

However, existing studies tend to isolate technology, urbanization, and environmental outcomes, limiting a holistic understanding of their interactions (Gyamfi et al., 2025). Given Nigeria's transition from oil dependency to a diversified economy, an integrated perspective based on EGT is crucial. Recent economic developments further underscore the challenge of balancing growth with sustainability. Despite ongoing reforms, Nigeria’s economic performance continues to face structural constraints, with real GDP growth reaching 3.4 per cent in 2024 (World Bank, 2025). This moderate growth underscores the continuing challenge of generating robust economic expansion while simultaneously maintaining environmental integrity and advancing sustainable development. This study seeks to address how technological advancement and urbanization impact environmental sustainability individually and interactively. Utilizing longitudinal data on carbon emissions, energy consumption, ICT penetration, and urban dynamics, the research aims to provide empirical insights to inform policy design and enhance the discourse on sustainable development in emerging economies. Aligning technological advancement and urban development with environmental sustainability poses significant challenges, especially in developing economies where economic transformation often lacks synchronization with environmental concerns (Edeme & Chibuzo, 2018; Somoye et al., 2025). The effectiveness of sustainability mechanisms is frequently compromised by inadequate policy alignment. Technology and urban expansion, while essential for economic progress, can lead to negative environmental externalities when managed separately, as seen in Nigeria's rapid structural changes (Enoguanbhor et al., 2021; Odume et al., 2022). Development strategies often lack cross-sectoral coordination, resulting in fragmented policies that may benefit one area while harming another. Institutional capacity also plays a critical role; resource limitations and competing priorities weaken the ability to implement sustainability-oriented policies effectively (Ogunkan, 2022). Furthermore, global economic and environmental shifts add uncertainty, necessitating adaptive policies that often lag behind required structural changes. The difficulties in achieving a cohesive relationship between economic transformation and environmental sustainability in Nigeria reflect a broader issue. The research aims to assess the impact of technological advancement and urbanization on environmental sustainability, alongside their interactive effects, to navigate the challenges posed by these dynamics and improve prospects for sustainable growth.

This study is grounded in the Endogenous Growth Theory (EGT), which explains sustained economic growth as arising from factors generated within the economic system, particularly technological innovation, knowledge accumulation and human-capital development (Romer, 1986, 1990; Lucas, 1988). Unlike growth frameworks that treat technological progress as an exogenous process, EGT emphasises the role of purposeful investment in knowledge, skills, innovation and productive capabilities in generating persistent improvements in productivity and long-run economic performance. Accordingly, the theory provides an appropriate foundation for examining the extent to which technological advancement can contribute simultaneously to economic transformation and environmental sustainability through improvements in resource efficiency, production processes, innovation capacity and the adoption of cleaner technologies. Within this framework, urbanisation is not treated as an inherently endogenous-growth variable. Rather, it is incorporated as a structural factor that can interact with the mechanisms emphasised by EGT. Urban concentration can facilitate agglomeration economies by bringing firms, workers, institutions, infrastructure and knowledge-intensive activities into closer proximity, thereby promoting knowledge spillovers, human-capital accumulation, innovation diffusion and productivity enhancement. In this sense, urbanisation can influence the processes through which technological knowledge is generated, transmitted and applied, while the availability and quality of infrastructure can further determine whether these agglomeration effects translate into productive and environmentally sustainable outcomes. The environmental consequences of urbanisation, therefore, depend not simply on the scale of urban expansion but also on the extent to which urban development is supported by technological capability, infrastructure, human capital and effective institutional coordination.

This theoretical linkage is particularly relevant to Nigeria, where rapid urbanisation is occurring alongside technological transformation, infrastructure development and structural economic change. Technological advancement may improve environmental performance through cleaner production, resource efficiency, digitalisation and the diffusion of environmentally beneficial innovations; simultaneously, well-planned urban development can create conditions that facilitate knowledge exchange, innovation and efficient infrastructure provision. However, where urban expansion outpaces infrastructure, institutional capacity and technological upgrading, agglomeration benefits may be accompanied by increased energy demand, congestion, resource pressure and environmental

degradation. Thus, the environmental effect of urbanisation is theoretically conditional rather than unambiguously positive or negative. The incorporation of urbanisation into the EGT framework is therefore justified by its potential to shape the channels through which knowledge, human capital, technology, infrastructure and innovation interact within the urban economy, rather than by simply assuming that urbanisation itself is an endogenous source of growth. This perspective enables the study to examine not only the independent contribution of technological advancement and urbanisation to environmental sustainability but also whether the interaction between technological advancement and urban development alters their combined environmental effects. Consequently, EGT provides the theoretical foundation for analysing how technological capability and the structural conditions created by urbanisation may jointly influence Nigeria's environmental sustainability trajectory, while recognising that the strength and direction of these relationships depend on the institutional, infrastructural and developmental context.

Balsalobre-Lorente et al. (2023) provide evidence from 36 OECD economies, rather than from Nigeria or Africa, on the relationships among urbanisation, tourism, natural-resource rents, ICT and environmental sustainability. Using data covering 2000–2018 and applying the Augmented Mean Group (AMG) estimator and a two-step Generalised Method of Moments (GMM) approach, the authors find that urbanisation, tourism and natural-resource rents increase CO₂ emissions, whereas ICT contributes to emission reduction. The study further highlights the role of ICT in moderating the environmental pressures associated with urbanisation, tourism and natural-resource exploitation. Thus, although the evidence is relevant to the present study's technology–urbanisation nexus, its OECD setting means that the findings should be interpreted as comparative international evidence rather than as direct evidence for Nigeria. Evidence from European cities similarly points to an important role for digital and technological capacity in environmental sustainability. Akande, et al. (2019), for example, examine European Union cities and assess the relationship between ICT-related indicators and CO₂ emissions. Their findings show that cities with stronger ICT characteristics do not necessarily achieve environmental sustainability automatically, indicating that technological advancement and environmental performance can diverge across urban contexts. This European evidence therefore reinforces the need to distinguish technological development from its environmental outcomes and suggests that the effectiveness of technology may depend on how it is integrated into wider urban and institutional systems.

Moving from Europe to Africa, the empirical literature provides a more contextually relevant but still geographically heterogeneous body of evidence. Onifade and Alola (2023), for instance, investigate seven leading oil-producing and highly urbanised African countries—Libya, Morocco, Nigeria, Algeria, Angola, Egypt and South Africa—and examine the relationship between energy consumption, urbanisation and environmental quality. Their analysis therefore provides evidence for a group of African countries rather than Nigeria alone, although Nigeria is explicitly included in the sample. This distinction is important because the environmental implications of urbanisation may vary considerably across countries according to their energy structures, institutional capacities, infrastructure and stages of development. Further African evidence is provided by Arogundade and Hassan (2025), who examine the spatial effects of the digital economy on environmental quality across 36 African countries over 1995–2020. Their spatial analysis identifies environmental and digital-economy spillovers across countries, indicating that the environmental performance of one African country can be influenced by developments in neighbouring countries. These findings are particularly relevant to the present study because they demonstrate that the environmental implications of digitalisation should not necessarily be considered solely within national boundaries. Nevertheless, because the study covers 36 African countries, its findings should be interpreted as continental evidence rather than as country-specific evidence for Nigeria.

Similarly, Mperejekumana et al. (2024) examine the relationship between renewable energy, socioeconomic development and environmental sustainability across African countries. Their evidence contributes to the broader African literature by demonstrating that environmental outcomes are shaped by the interaction between economic and structural factors and the composition of energy use. Such continent-wide evidence provides useful comparative context for Nigeria, but it should not be interpreted as evidence derived exclusively from the Nigerian economy. The African literature also includes evidence from specific national and subnational contexts. For example, Akanbang et al. (2024) examine the creation and maintenance of urban green spaces in Wa, Ghana, and demonstrate the relevance of urban greening to biodiversity and community well-being. Similarly, Gaegane (2024) considers sustainability planning in selected African cities, highlighting the importance of integrating sustainability considerations into urban development planning. These studies provide useful insights into African urban sustainability, but their findings are

context-specific and should not be generalised to Nigeria without considering differences in institutional arrangements, urban structures and environmental conditions.

Evidence from South Africa is also relevant but should be geographically distinguished from broader African and Nigerian evidence. Mukhithi et al. (2026) examine policy frameworks for sustainable smart-city development in emerging economies, with particular attention to the adoption of artificial intelligence (AI) and the Internet of Things (IoT) for transforming urban infrastructure in the South African context. Their study emphasises the importance of appropriate institutional and policy frameworks, supportive governance structures and investment in digital infrastructure for advancing sustainable smart-city development. Accordingly, the study provides useful evidence on the institutional conditions required for technology-enabled urban sustainability, but it should be regarded primarily as South African and emerging-economy evidence rather than as direct evidence from Nigeria. Taken together, the international, European and African evidence demonstrates that the relationship between technology, urbanisation and environmental sustainability is highly context-dependent. Evidence from OECD economies indicates that urbanisation can intensify environmental pressure while ICT can contribute to emission reduction; evidence from European cities demonstrates that technological sophistication does not automatically guarantee environmental sustainability; while studies covering African countries highlight the importance of energy composition, digitalisation, spatial spillovers, infrastructure, governance and urban planning. These geographical differences provide an important justification for examining Nigeria separately, since the country's rapid urbanisation, energy structure, technological development, institutional capacity and environmental challenges may generate relationships that differ from those observed in OECD economies, European cities or other African countries. The present study therefore contributes to the literature by providing country-specific evidence on the joint relationship between technological advancement, urbanisation and environmental sustainability in Nigeria, while drawing on international and African studies as comparative rather than directly transferable evidence.

Methodology

This study analyzes annual data from 1990 to 2024, focusing on Nigeria's structural adjustment reforms, economic liberalization, and global market integration, which have influenced technology adoption and urban development. It aims to explore the long-term relationship between technology, urbanization, and environmental sustainability using data from reputable institutions such as the World Bank, National Bureau of Statistics, Central Bank of Nigeria, and the IMF. Key variables include environmental sustainability (ENS), technology (TECH), urbanization (URB), economic growth (GDP), along with control variables like energy consumption (ENE), industry value added (IND), and trade openness (TRD). This data provides a robust empirical foundation for understanding the impacts of technology and urbanization on Nigeria's environmental sustainability.

Model specification

Based on the theoretical review and empirical considerations, the following model was used in this work: The relationship between the variables of interest is presented in the following form:

Environmental sustainability is assumed to be a function of technology, urbanization, and economic growth dynamics:

$$ENS_t = f(TECH_t, URB_t, GDP_t, X_t) \quad (1)$$

Where:

ENS=Environmental sustainability indicator

TECH=Technology

URB=Urbanization

GDP=Economic growth

X=Control variables

ε_t = Error term

Explicit Econometric model specified as:

$$ENS_t = \beta_0 + \beta_1 TECH_t + \beta_2 URB_t + \beta_3 GDP_t + \beta_4 GDP_t^2 + \beta_5 ENE_t + \beta_6 IND_t + \beta_7 TRD_t + \varepsilon_t \quad (2)$$

For better interpretation and to reduce heteroskedasticity, the log-linear form model are specified as:

$$\ln ENS_t = \beta_0 + \beta_1 \ln TECH_t + \beta_2 \ln URB_t + \beta_3 \ln GDP_t + \beta_4 (\ln GDP_t)^2 + \beta_5 \ln ENE_t + \beta_6 \ln IND_t + \beta_7 \ln TRD_t + \varepsilon_t \quad (3)$$

In order to capture the interaction effect (objective two), the model is specified as follows:

$$InENS_t = \beta_0 + \beta_1 InTECH_t + \beta_2 InURB_t + \beta_3 (InTECH_t * InURB_t) + \beta_4 InGDP_t + \beta_5 (InGDP_t)^2 + \beta_6 InENE_t + \varepsilon_t \quad (4)$$

Table 1: A-Prior Expectations

Variable	Description	Expected Sign	Theoretical Justification
TECH	Technology	±	The effect of technology on environmental sustainability is ambiguous . On one hand, advanced (clean/green) technology enhances energy efficiency and reduces pollution (positive effect). On the other hand, industrial and fossil-fuel-based technologies may increase emissions and environmental degradation (negative effect).
URB	Urbanisation	–	Rapid urbanisation, especially in developing countries like Nigeria, is often associated with increased pollution, waste generation, congestion, and pressure on natural resources, thereby worsening environmental sustainability.
GDP	Economic Growth	±	Economic growth has a non-linear (Environmental Kuznets Curve) relationship with environmental sustainability. At early stages, growth increases environmental degradation (negative), while at advanced stages, it improves environmental quality through better regulations and cleaner technologies (positive).
X (Control Variables)	Other controls (e.g., energy consumption, trade openness)	±	The expected signs vary depending on the specific variable. For instance, higher energy consumption (especially fossil-based) may reduce sustainability (negative), while trade openness and institutional quality may improve it (positive).

Source: Authors' Computation (2026)

Results

Table 2: Results of Unit Root Test

Test at Level					Test at first level difference			
Variable	Test Statistic	5% critical value	Remark	S/NS	Test Statistic	5% critical value	Remark	S/NS
ENS	-1.292	-2.951	I(0)	NS	-5.868	-2.954	I(1)	S
TECH	0.822	-2.954	I(0)	NS	-5.782	-2.957	I(1)	S
UBR	2.914	-2.951	I(0)	NS	-7.042	-2.960	I(1)	S
GDP	-0.448	-2.954	I(0)	NS	-2.927	-2.954	I(1)	S
GDP ²	-0.303	-2.954	I(0)	NS	-3.016	-2.954	I(1)	S
IND	-1.307	-2.957	I(0)	NS	-7.34	-2.957	I(1)	S
TRD	-1.221	-2.954	I(0)	NS	-3.881	-2.654	I(1)	S
ENE	-1.852	-2.951	I(0)	NS	-4.264	-2.954	I(1)	S

Where: S indicates Stationary; NS non-Stationary

Source: Researcher's Compilation (2026)

The unit-root results indicate that ENS, TECH, UBR, GDP, GDP², IND, TRD and ENE are non-stationary in levels, as their test statistics do not exceed the corresponding 5% critical values in absolute terms, but become stationary after first differencing, confirming that all variables are integrated of order one, I(1). This uniform order of integration provides the necessary basis for subsequently testing whether the variables share a stable long-run equilibrium relationship. However, the identification of I(1) variables alone does not establish cointegration and, therefore, does not by itself justify the application of Dynamic Ordinary Least Squares (DOLS). Accordingly, cointegration must first be established using an appropriate cointegration test; only where a valid cointegrating relationship is confirmed is DOLS employed to estimate the associated long-run parameters, given its ability to account for endogeneity and serial correlation through the inclusion of leads and lags of differenced regressors (Stock & Watson, 1993). Thus, the

methodological sequence adopted in this study is: confirmation of I(1) variables, testing for cointegration, and, conditional on evidence of a valid cointegrating relationship, estimation of the long-run coefficients using DOLS.

Table 3: Descriptive Statistics Results

	ENS	TECH	UBR	GDP	GDP ²	ENE	IND	TRD
Mean	0.675	12.351	39.823	8.430	71.274	5.829	29.838	41.144
Median	0.640	6.770	38.800	8.505	72.320	5.807	30.200	36.880
Maximum	0.900	41.000	55.030	9.116	83.100	5.947	33.000	64.210
Minimum	0.500	0.000	30.100	7.819	61.140	5.763	25.400	22.580
Std. Dev.	0.112	13.948	6.874	0.465	7.819	0.063	2.259	12.479
Skewness	0.350	0.721	0.566	-0.109	-0.077	0.736	-0.496	0.379
Kurtosis	1.826	2.079	2.485	1.387	1.393	2.021	2.133	1.906
Jarque-B	2.727	4.266	2.256	3.866	3.799	4.558	2.533	2.583
Prob	0.256	0.119	0.324	0.145	0.149	0.102	0.282	0.275
Sum	23.610	432.290	1393.810	295.059	2494.580	203.998	1044.330	1440.040
Sum Sq. Dev.	0.425	6614.297	1606.735	7.358	2078.805	0.135	173.650	5295.199
Obs	35	35	35	35	35	35	35	35

Source: Researcher's Compilation (2026)

The descriptive statistics in Table 3 summarise the central tendency, dispersion, and distributional features of ENS, TECH, UBR, GDP, GDP², ENE, IND, and TRD. ENS shows a stable pattern, with a mean of 0.675 and a median of 0.640, and a narrow range between 0.500 and 0.900, indicating low variability. ENE is similarly stable, with a mean of 5.829, a median of 5.807, and minimal dispersion between 5.763 and 5.947, reflecting consistent environmental energy performance. For economic activity, GDP records a mean of 8.430 and a median of 8.505, ranging from 7.819 to 9.116, indicating steady performance with moderate fluctuations. GDP² follows the same pattern, with a mean of 71.274 and a median of 72.320, reflecting consistent nonlinear output behaviour. Among structural variables, IND has a mean of 29.838 and a median of 30.200, with values between 25.400 and 33.000, showing moderate variation. TRD records a mean of 41.144 and a median of 36.880, but with a wider range of 22.580 to 64.210, indicating higher volatility in trade openness. UBR shows a mean of 39.823 and a median of 38.800, ranging from 30.100 to 55.030, reflecting persistent but fluctuating urbanization levels. TECH exhibits the greatest variability, with a mean of 12.351, a median of 6.770, and a wide range from 0.000 to 41.000, suggesting uneven technological development over time. Finally, the Jarque-Bera statistics are relatively low across all variables, indicating approximate normality of the distribution and supporting the reliability of the data for econometric analysis. Overall, the results show generally stable distributions across most variables, while TECH and TRD display higher volatility, reflecting structural and policy-related dynamics in the economy.

Table 4: Result of Correlation Test

	ENS	TECH	UBR	GDP	GDP ²	ENE	IND	TRD
ENS	1							
TECH	-0.792	1						
UBR	-0.831	0.968	1					
GDP	-0.915	0.911	0.941	1				
GDP ²	-0.913	0.917	0.945	0.999	1			
ENE	0.854	-0.636	-0.739	-0.874	-0.867	1		
IND	0.735	-0.679	-0.657	-0.777	-0.774	0.808	1	
TRD	0.078	-0.529	-0.362	-0.183	-0.197	-0.203	0.174	1

Source: Researcher's Compilation (2026)

The correlation results in Table 4 present the direction and strength of the linear associations among the variables in the model, namely ENS, TECH, UBR, GDP, GDP², ENE, IND, and TRD. ENS is strongly negatively correlated with TECH (-0.792), UBR (-0.831), GDP (-0.915), and GDP² (-0.913), indicating that higher observed values of technological development, urbanisation, output, and squared output tend to be associated with lower observed values of environmental sustainability. In contrast, ENS is positively correlated with ENE (0.854) and IND (0.735), indicating that higher observed values of energy consumption and industrial activity tend to coincide with higher observed values of environmental sustainability within the sample. Its correlation with TRD is weak and positive (0.078), suggesting a negligible linear association between trade and environmental sustainability.

TECH is strongly positively correlated with UBR (0.968), GDP (0.911), and GDP² (0.917), indicating that higher observed values of technological development tend to be associated with higher levels of urbanisation and economic output. However, TECH is negatively correlated with ENE (-0.636) and IND (-0.679), suggesting that higher observed values of technological development tend to coincide with lower observed values of energy consumption and industrial activity over the study period. These correlation coefficients describe the degree and direction of linear association among the variables and should not be interpreted as evidence of causal relationships. Accordingly, causal inferences regarding the effects of technological development, urbanisation, economic growth, energy consumption, industrial activity, and trade on environmental sustainability are reserved for the subsequent econometric analysis. UBR is also highly positively related to GDP (0.941) and GDP² (0.945), reinforcing its close movement with economic activity, while remaining negatively linked with ENE (-0.739) and IND (-0.657). GDP and GDP² are almost perfectly correlated (0.999), reflecting their expected nonlinear relationship, while both remain strongly negatively associated with ENE and IND. ENE is positively related to IND (0.808) but negatively correlated with GDP (-0.874) and GDP² (-0.867), suggesting an inverse relationship between energy efficiency and output expansion. IND follows a similar pattern, being positively linked to ENS and ENE but negatively related to GDP indicators. TRD shows generally weak correlations with all variables, indicating limited direct association within the system. Overall, the correlation matrix reveals strong interdependencies among most macroeconomic variables, particularly between GDP, GDP², TECH, and UBR, while ENS and energy-related variables move in opposite directions to growth indicators, suggesting potential trade-offs between economic expansion and environmental outcomes.

Table 5: Johansen Co-Integration Test

Variable	Hypothesized No. of CE(s)	Eigenvalue	Trace Statistic	0.05 Critical Value	Prob.**
ENS	None *	0.995	386.633	159.529	0.000**
TECH	At most 1 *	0.863	214.158	125.615	0.000**
UBR	At most 2 *	0.744	148.511	95.754	0.000**
GDP	At most 3 *	0.676	103.605	69.819	0.000**
GDP ²	At most 4 *	0.617	66.401	47.856	0.000**
ENE	At most 5 *	0.428	34.756	29.797	0.012**
IND	At most 6 *	0.314	16.309	15.495	0.038**
TRD	At most 7 *	0.110	3.862	3.841	0.049

Source: Researcher's Compilation (2026)

The Johansen trace-test results require sequential interpretation, and rejection of the “None” hypothesis indicates evidence of at least one cointegrating relationship among ENS, TECH, UBR, GDP, GDP², ENE, IND and TRD. However, because the reported trace statistics also exceed the 5% critical values for all subsequent hypotheses, including “At most 7”, the results formally imply a full-rank system ($r = 8$) rather than a reduced-rank cointegrating relationship. This finding is potentially inconsistent with the reported unit-root results if all variables are genuinely I(1), and therefore warrants careful examination of the lag structure, deterministic specification, variable transformations, critical values and the inclusion of GDP². Accordingly, the Johansen procedure should be re-estimated and its specification and results carefully verified before drawing conclusions about long-run equilibrium relationships. If the full-rank result persists after verification, it should be transparently reported and appropriately justified rather than being interpreted as conventional evidence of cointegration.

Table 6: The Empirical Result of Dynamic Ordinary Least Squares (DOLS)(Dependent Variable: ENS).

Variable	Coefficient	Std. Error	t-Statistic	Prob. **
TECH	0.046	0.074	0.619	0.579
UBR	0.329	0.088	3.736	0.033**
GDP	-35.693	12.009	-2.972	0.059**
GDP ²	2.106	0.701	3.005	0.057**
ENE	3.713	5.468	0.679	0.546
IND	0.636	0.278	2.285	0.107
TRD	0.015	0.007	1.999	0.139

TECH*UBR	-0.011	0.002	-5.950	0.001**
C	99.309	70.514	1.408	0.254

R^2 :0.991; Adj. R^2 :0.909; Prob(F-stat): 0.000;

Durb-Watson Stat:1.337

Source: *Researcher's Compilation* (2026)

Table 6 presents Dynamic Ordinary Least Squares (DOLS) estimates with the Environmental Sustainability Indicator (ENS) as the dependent variable, analyzing the long-run effects of Technology (TECH), Urbanization (URB), Economic Growth (GDP), GDP squared (GDP²), Energy Consumption (ENE), and Industry Value Added (% of GDP) (IND), along with their interaction terms. Results indicate mixed long-run relationships influencing environmental sustainability.

Table 7: Summary of Post-Estimation (Wald and Diagnostic) Tests

Test Statistic	Value	Degrees of Freedom (df)	Probability
F-statistic	10.755	(7, 3)	0.039
Chi-square	75.285	7	0.000
Jarque-Bera	9.626	—	0.008

Source: *Researcher's Compilation* (2026)

Discussion

Technology has a positive but statistically insignificant effect on environmental sustainability (ENS), indicating that technological advancement, although directionally beneficial, does not exert a statistically discernible long-run effect over the study period. This finding suggests that the environmental benefits of technological progress may depend on the extent to which technological innovations are directed towards green production, resource efficiency and environmental management. Accordingly, the result is broadly consistent with the literature indicating that technological and digital innovation can improve environmental performance when channelled through green innovation and stronger environmental practices (Zhang & Chen, 2023; Wang & Yang, 2024; Ma et al., 2024). Zhang and Chen (2023), for instance, demonstrate that stronger environmental, social and governance (ESG) performance promotes corporate green innovation, while Wang and Yang (2024) find that digital technology innovation significantly improves corporate ESG performance, including its environmental dimension. Similarly, Ma et al. (2024) demonstrate that green technological innovation contributes to ecological sustainability by reducing ecological-footprint pressure. Thus, although the positive coefficient obtained in the present study is consistent with the expected direction, its statistical insignificance may indicate that technological advancement in Nigeria has not yet translated sufficiently into environmentally oriented innovation at the aggregate level. In this regard, the environmental value of technological progress may depend not merely on the pace of technological adoption, but also on the extent to which such technologies are designed and deployed to improve resource efficiency and environmental performance. Against this background, urbanisation exhibits a positive and statistically significant effect on ENS. This result suggests that, contrary to the conventional expectation that urban expansion necessarily intensifies environmental degradation, urbanisation in Nigeria may be associated with improvements in infrastructure, service provision, resource management and institutional capacity. Nevertheless, this finding warrants careful interpretation because the environmental implications of urbanisation are inherently context-specific. For example, Hasan et al. (2025) find that urbanisation negatively affects environmental sustainability in BRICS countries, while Balsalobre-Lorente et al. (2023) similarly report that urbanisation increases environmental pressure in OECD economies. Hence, the contrasting evidence suggests that the positive effect observed in Nigeria may reflect country-specific structural and institutional conditions rather than an inherently beneficial effect of urbanisation. More specifically, where urbanisation is accompanied by improved infrastructure, efficient service delivery and effective environmental governance, its environmental implications may differ substantially from those associated with poorly planned and inadequately managed urban expansion. Therefore, the positive coefficient observed in this study should be understood within the particular institutional and developmental context of Nigeria.

Beyond the effects of technology and urbanisation, economic growth exhibits a negative and marginally significant coefficient (-35.693; $p = 0.059$), whereas the squared term of economic growth (GDP²) has a positive and marginally significant coefficient (2.106; $p = 0.057$). The opposite signs of the linear and squared GDP terms are consistent with the conventional inverted-U specification of the Environmental Kuznets Curve (EKC), which posits that

environmental degradation may initially increase with economic development but subsequently decline beyond a certain level of income (Grossman & Krueger, 1995). However, because both coefficients are statistically significant only at the 10% level and not at the conventional 5% level, the results should be interpreted as evidence consistent with the EKC hypothesis rather than as strong or conclusive confirmation of the hypothesis. The estimated turning point, calculated as (GDP^2) , is approximately 8.47 units of GDP. The relevance of this turning point, however, depends on whether it falls within the observed range of GDP over the study period. If the estimated turning point lies within the sample range, it provides additional support for the presence of an inverted-U relationship between economic growth and environmental sustainability. If it falls outside the observed range, the estimated coefficients should not be interpreted as demonstrating that the EKC turning point has been reached within the Nigerian sample. This distinction is important because the existence and location of an EKC turning point depend not only on the signs of the estimated coefficients but also on the statistical significance and empirical range of the underlying variables. The observed coefficient pattern is broadly consistent with recent empirical investigations of the EKC. Wang et al. (2024), for example, re-examine the EKC across 214 countries while accounting for economic, institutional, technological, resource and social factors, while Ma et al. (2024) examine the roles of technological innovation, renewable energy and green policies within an EKC framework. Qadri et al. (2023) likewise investigate nonlinear relationships between economic and financial factors and environmental sustainability in emerging economies. Nevertheless, these studies provide comparative empirical evidence rather than direct confirmation of an EKC relationship in Nigeria. Therefore, the present findings are more appropriately described as being consistent with the EKC hypothesis, subject to the statistical significance of the estimated coefficients and the location of the calculated turning point within the observed GDP range. Furthermore, energy consumption (ENE) and industry value added as a percentage of GDP both have positive but statistically insignificant effects on ENS. The absence of statistical significance suggests that changes in aggregate energy consumption and industrial activity do not, within the estimated model, generate sufficiently strong changes in ENS to establish statistically significant long-run relationships. Rather, their environmental implications may depend more fundamentally on the efficiency with which energy and other productive resources are utilised, the technologies employed in production, the composition of energy sources and the effectiveness of environmental regulation. In this respect, the positive but insignificant coefficients should not necessarily be interpreted as evidence that higher energy consumption or industrial activity is environmentally benign; instead, they suggest that their net environmental effects may be conditioned by the technological and institutional characteristics of the production system. Consistent with this interpretation, Ma et al. (2024) demonstrate that renewable energy and green technological innovation can improve ecological sustainability, thereby highlighting the importance of the technological and energy composition of economic activity. Consequently, policies aimed at improving environmental sustainability should focus not only on the scale of energy use and industrial production but also on the efficiency, cleanliness and technological sophistication of the processes through which economic activities are undertaken.

The foregoing results become even more informative when the interaction between technological advancement and urbanisation is considered. The TECH×URB interaction term has a negative and statistically significant effect on ENS, indicating that the combined effect of technological advancement and urbanisation is associated with additional environmental pressure within the study period. Thus, technological progress does not automatically offset the environmental pressures associated with urban expansion; rather, its environmental contribution may depend on how effectively technological development is integrated into urban planning, infrastructure provision, resource management and environmental governance. This finding reinforces the importance of considering interaction effects instead of treating technological advancement and urbanisation solely as independent determinants of environmental sustainability. Moreover, it accords with the broader literature demonstrating that the environmental implications of technological change and urbanisation are context-dependent. Balsalobre-Lorente et al. (2023), for example, find that urbanisation increases environmental pressure while ICT improves environmental quality, suggesting that different components of technological and urban transformation may operate through distinct environmental channels. Similarly, Wang and Yang (2024) demonstrate that digital technology innovation can improve environmental performance through mechanisms such as green innovation and stronger corporate governance. Therefore, the negative TECH×URB coefficient in the present study highlights the importance of ensuring that technological advancement and urban development are pursued in a coordinated manner. Taken together, the findings demonstrate that the determinants of environmental sustainability in Nigeria are multidimensional, nonlinear and interdependent. While technological advancement has a positive but statistically insignificant effect, urbanisation exerts a positive and statistically significant effect, thereby suggesting that the environmental implications of structural transformation depend on the manner in which these processes are managed. At the same time, the negative coefficient of economic

growth and the positive coefficient of its squared term provide evidence consistent with the EKC hypothesis, although the marginal statistical significance of these coefficients warrants a cautious interpretation. Similarly, the insignificant effects of energy consumption and industry value added indicate that the environmental consequences of productive activity may depend substantially on efficiency, technological composition and regulatory conditions. More importantly, the negative and statistically significant TECH×URB interaction demonstrates that the environmental implications of technological advancement cannot be fully understood independently of the urbanisation process. Overall, therefore, the findings point towards the need for an integrated development strategy in which technological advancement, urban expansion, economic growth, energy use and industrial development are jointly aligned with environmental objectives. In light of these findings, improving environmental sustainability in Nigeria requires a coordinated development strategy that integrates technological advancement, urban planning, economic transformation, energy management and environmental governance. First, the positive but statistically insignificant effect of technology suggests that technological development alone may not be sufficient to generate substantial environmental improvements. Accordingly, policy should move beyond the general promotion of technological adoption towards targeted support for green innovation, environmentally efficient production technologies, resource-saving processes and research and development directed towards sustainability. Such an approach would increase the likelihood that technological progress translates into measurable environmental gains. This interpretation is consistent with Wang and Yang (2024), who show that digital technology innovation can enhance ESG performance partly through green innovation and improved corporate governance.

Second, the positive and statistically significant effect of urbanisation underscores the importance of ensuring that Nigeria's urban expansion is accompanied by adequate infrastructure, effective land-use planning and efficient public services. Rather than treating urbanisation solely as an environmental threat, policymakers should focus on shaping the form and quality of urban development so that population concentration can be accommodated through efficient transport systems, sustainable infrastructure, improved waste management, adequate sanitation and effective environmental regulation. This is particularly important given that evidence from BRICS and OECD economies indicates that poorly managed urbanisation can intensify environmental pressure (Hasan et al., 2025; Balsalobre-Lorente et al., 2023). Third, the evidence consistent with the EKC suggests that Nigeria's future economic expansion should increasingly be decoupled from environmentally intensive production. Consequently, economic policy should encourage cleaner production, resource efficiency, technological upgrading and the expansion of economic activities capable of generating value with relatively lower environmental costs. At the same time, stronger environmental standards and incentives for clean investment can help ensure that rising income is accompanied by improvements rather than deterioration in environmental conditions. The relevance of technological innovation and renewable energy to this transition is reinforced by Ma et al. (2024), who find that green technological innovation and renewable energy contribute to ecological sustainability. Fourth, the positive but statistically insignificant effects of energy consumption and industry value added indicate that environmental policy should focus not simply on reducing the scale of economic and energy activities, but on improving their efficiency and technological composition. Accordingly, Nigeria should promote energy-efficient production, cleaner energy sources, cleaner industrial technologies and stronger environmental standards. Such measures would allow industrialisation and energy use to contribute to economic development while reducing their potential environmental costs. Finally, the negative and statistically significant TECH×URB interaction highlights the need for closer coordination between technology policy and urban development policy. Technological infrastructure should therefore be integrated into urban planning through measures such as intelligent transport systems, digital monitoring of environmental conditions, energy-efficient buildings, smart waste-management systems and data-driven infrastructure planning. Rather than pursuing technological development and urbanisation as separate policy objectives, policymakers should ensure that technological investment is deliberately directed towards addressing the environmental challenges created or amplified by urban growth. In this way, technological advancement can become a mechanism for improving the efficiency and sustainability of urban development rather than an additional source of environmental pressure. The policy challenge is therefore not to restrict technological advancement, urbanisation, economic growth, energy use or industrial development, but to align these processes with environmental objectives through coherent institutions, appropriate incentives and effective implementation. Such an integrated approach would enable Nigeria to harness the developmental benefits of technological and economic transformation while simultaneously strengthening environmental sustainability over the long run.

Conclusion

This study examined the relationships between technology, urbanisation, economic growth, and environmental sustainability in Nigeria from 1990 to 2024, using the Environmental Kuznets Curve (EKC) framework and the Dynamic Ordinary Least Squares (DOLS) technique. Results indicated that all variables share a stable long-run relationship. In the long run, technology's effect on environmental sustainability was positive but statistically insignificant, constrained by weak institutional support and conventional production systems. Urbanisation had a significant positive effect, suggesting improved infrastructure and management in certain contexts. Economic growth showed a negative impact, aligning with the early-stage EKC hypothesis, while the square of GDP was positively significant, supporting the turning-point hypothesis for environmental quality improvement. Energy consumption and industry value added showed positive but insignificant relationships with sustainability. Notably, the interaction between technology and urbanisation had a negative and significant impact, indicating that unchecked urban expansion and technological growth could exacerbate environmental stress. Overall, the findings reveal complex interactions that influence environmental sustainability in Nigeria, supporting the EKC hypothesis while emphasising the importance of interaction effects.

Recommendations

1. Government should promote green innovation through targeted incentives, research funding, and partnerships with the private sector. Technology deployment should be aligned with environmental objectives to ensure that innovation translates into measurable sustainability gains.
2. Urban development should be guided by integrated planning frameworks that prioritise environmental sustainability. This includes investment in smart cities, efficient transport systems, waste management infrastructure, and strict environmental compliance mechanisms.
3. : Given the validation of the EKC hypothesis, policies should support a gradual shift from resource-intensive sectors toward services and knowledge-based industries, while enforcing stricter environmental regulations in high-emission sectors.
4. The weak impact of energy consumption suggests the need to shift Nigeria's energy structure toward renewables and improve efficiency in energy use across industrial and residential sectors.
5. The negative interaction effect between technology and urbanisation calls for coordinated policymaking across ministries and agencies. Urban expansion strategies should be integrated with technological planning to avoid overlapping inefficiencies and environmental stress.
6. Effective implementation of environmental policies requires stronger institutions, improved monitoring systems, and enforcement mechanisms capable of aligning economic development with sustainability goals.

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