

Urbanization-ICT Nexus and Environmental Sustainability in West African Countries: A Cross-Sectional ARDL Approach

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Abstract

Studies have shown that urbanization presents a unique opportunity to drive economic growth and improve living standards, but it also poses significant environmental sustainability challenges. Evidence suggests that harnessing digital technologies have the potential to radically transform urban centers into smart cities, thereby addressing sustainability challenges. This study, therefore, examines the relationship between urbanization, ICT, and environmental sustainability in West Africa, employing a Cross-Sectional Autoregressive Distributed Lag (CS-ARDL) model. The empirical findings reveal a monotonic relationship between urbanization and environmental sustainability in the selected West African countries. The results suggest that rapid urbanization is likely to lead to environmental degradation, meaning that as cities expand, environmental quality tends to decline. Moreover, the interactive analysis reveals that urbanization and ICT exert a positive and significant effect on environmental sustainability, suggesting that ICT serves as a moderating force: although urbanization on its own harms the environment, the negative effect of urbanization is reduced when ICT increases alongside urban growth. In addition, the findings reveal that ICT and GDP per capita have a significant effect on environmental sustainability in the long run. The nonlinear and positive effect of ICT and GDP per capita significantly enhance environmental sustainability. Thus, provides evidence in support of the EKC hypothesis for the selected West African countries. Accordingly, to enhance environmental sustainability in these countries, policymakers should design policies to promote ICT within sustainable energy frameworks, improve institutional quality, and facilitate the transition to a circular economy. These strategies are crucial for ensuring that urbanization and digital advancement contribute to long-term environmental sustainability in West Africa.

Keywords: Economic expansion, Environmental sustainability, ICT, Sustainable Development, Urbanization

Introduction

The connections between urbanization and the environment have been a long-standing debate, and it is far beyond the scope of the literature review. Despite the evident and continuing interest in urban population-environment links, the direct interplay of urban population dynamics and

environmental change is difficult to identify and even more difficult to quantify. On one hand, the argument is frequently voiced that the population usually aggregates urban population growth, which has a substantial (and adverse) effect on environmental quality. On the other hand, some dispute the overall claims of the degree of anthropogenic impacts on the environment (De Sherbiniin et al., 2009). According to Radoire et al (2022), urbanization indeed has environmental impacts at various phases of its development, with the overall impact being difficult to estimate. The transition theory contended that when civilization moves to an industrial-based economy, air pollution rises along with urban prosperity. Thus, the economic expansion over a sustainable environment concern may worsen, but with increased environmentally-friendly technological innovation, environmental deterioration declines, and environmental sustainability increases (Radoire et al, 2022).

Research highlights that urbanization is a major driver of energy use, with significant implications for CO₂ emissions (Adedoyin, Alola & Bekun 2020; Shahbaz, Balsalobre-Lorente & Sinha 2019; Radoine et al., 2022; Khan & Majeed, 2023). Fossil fuel combustion and pollution from waste sources are closely linked to total energy consumption and energy structure, which are the primary causes of CO₂ emissions (Posu et al., 2024). The rapid increase in urban populations intensifies the demand for resources and infrastructure, further straining the natural environment.

Urbanization in Africa has significantly contributed to economic development, creating jobs, attracting investment, and fostering industrialization. Between 1990 and 2015, approximately 4,500 new cities emerged in Africa, offering rural migrants access to jobs, services, and infrastructure (OECD/UN ECA/AfDB, 2022). However, while urbanization drives economic growth, it also increases resource consumption and pollution. In West Africa, large cities like Lagos (Nigeria), Accra (Ghana), and Dakar (Senegal) have emerged as megacities, experiencing population surges and heightened economic activity (Abdulkadir, et. al. 2025, African Policy Circle, 2020). From 1990 to 2022, West Africa's urban population grew from 54.5 million to 207.3 million, with projections indicating it could reach 277.9 million by 2030 (OWID, 2024). This urban growth is fueled by agglomeration economies, which enhance productivity and account for about 29% of Africa's annual GDP growth from 2001 to 2020 (OECD/UN ECA/AfDB, 2022; World Bank, 2018). However, the rapid expansion of urban areas has led to increased industrial

activities, high vehicular emissions, and heightened pollution levels, particularly air pollution, which poses serious public health risks.

In response to these challenges arising from urbanization, the adoption of Information and Communication Technologies (ICTs) has been proposed as a viable solution for reducing CO₂ emissions (Radoine et al., 2021). ICTs play a crucial role in addressing environmental issues by promoting energy efficiency, enhancing waste management, and facilitating the development of smart cities. ICTs also support e-commerce, teleworking, and e-conferencing, which minimize transportation-related CO₂ emissions (Qayyum, Zhang, Ali & Kirikkaleli, 2024).

2. Theoretical Background and Literature Review

Debates about the long-term drivers of urban development and environmental protection have been shaped by two major frameworks: the Ecological Modernization Theory (EMT) and the Environmental Kuznets Curve (EKC). Both perspectives describe a non-linear (inverted U-shaped) relationship between development and environmental quality, but they differ in focus. The EKC argues that environmental improvement occurs at higher income levels when wealthier societies can afford cleaner technologies. In contrast, EMT attributes environmental improvement not simply to income, but to deeper structural changes—technological innovation, institutional reform, and shifts in societal behaviour.

Since emerging in the 1980s, EMT has influenced policy agendas and environmental sociology, but not without criticism. Mol (1995) argues that EMT lacks strong analytical tools for explaining institutional ecological restructuring and suggests network analysis as a better lens for examining policy and institutional transformation. Ewing (2017) further critiques EMT for relying too heavily on profit-driven modernization, claiming that its "green capitalist" assumptions ultimately undermine its environmental solutions. He calls for theories that challenge the deeper structures of the global capitalist system. To understand development–environment linkages, scholars rely on two analytical perspectives: the growth–environment trade-off and the technological–innovation lens.

Under the growth–environment lens, the trade-off can be either monotonic or non-monotonic. The monotonic view suggests a linear relationship—economic growth consistently increases environmental degradation. Evidence from many studies supports this pattern, showing that CO₂

emissions rise steadily with income (Miah et al, 2011; Arouri et al. 2014; Adebayo et al. 2021). The non-monotonic view is captured by the EKC hypothesis, which suggests an inverted U-shaped link between growth and pollution: environmental degradation worsens in early stages of income growth but improves after a turning point. Numerous studies support this pattern under different contexts and methods (Halkos & Gkampoura, 2021; Patrícia & António, 2022)), but overall findings remain mixed and sometimes contradictory.

The technological–innovation perspective examines how modernization via clean technologies, renewable energy, and innovation capacity can decouple economic or urban growth from environmental degradation. This approach argues that cities can grow while pollution declines, provided they adopt energy-efficient technologies, expand renewables, and invest in innovation systems. Empirical evidence shows partial or full decoupling in many contexts, especially when strong policies and innovation thresholds are in place (Kreij & Margellos, 2022; Wei et al., 2023; Dahmani et al., 2021; Li & Cao, 2025; Bouattour et al., 2025).

3. Research Design and Data Description

3.1 Data Source

This study uses a panel dataset of 12 West African countries from 1999 to 2024. This is due to data availability constraints for some key variables. The main variables include urban population growth, ICT-related variables (such as mobile cellular subscriptions, fixed broadband subscriptions, active mobile broadband subscriptions, individuals using the Internet, and households with Internet access at home), and environmental metrics (ecological footprints and material footprints). The data were sourced from World Justice Project (2024), World Bank's World Development Indicators (2025), Global Footprint Network (2025), and Ourworldindata (2025).

3.2 Model Construction

3.2.1 The direct impact of urbanization-ICT nexus on environmental sustainability

Following the theoretical framework for this study, the direct impact of urbanization-ICT nexus on environmental sustainability can be analyzed through a monotonic linear relationship, which specifies environmental sustainability as a function of urbanization, ICT development and other variables. It is stated as follows:

$$ESI_{it} = \alpha_i + \gamma_t + \beta_1 URBPOP_{it} + \beta_2 ICT_{it} + \beta_3 (URBPOP_{it} * ICT_{it}) + \beta_4 GDPpcit + \beta_5 CTVit + \varepsilon_{it} \quad (1)$$

Where ESI represents the Environmental Sustainability Index, measured using both the ecological footprint and material footprint. These indicators together provide a more comprehensive picture of human pressure on the environment by capturing production and consumption-based emission. Urbanization (URBPOP) is measured using the urban population growth rate, while ICT represents information and communication technology penetration. GDPPC refers to per capita GDP growth, used as an indicator of economic affluence. The model also includes a set of control variables (CTV): industrial value-added, energy consumption (in terawatt-hours), trade openness, and an institutional quality index. The interaction term URBPOP*ICT is included to showing whether technological adoption moderates the environmental impacts of urban growth

The subscript *i* refers to each country, while *t* represents the time dimension (years). The term α_i captures country-specific fixed effects—factors such as geography, historical institutions, and cultural characteristics that do not change over time. γ_t represents time fixed effects, accounting for global shocks or trends affecting all countries in a given year. The coefficients β_1 to β_4 represent the parameters to be estimated, and ε_{it} is the stochastic error term. We expect $\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 > 0$, then higher ICT can reduce or reverse the negative marginal effect of urbanization. At sufficiently high ICT: $\beta_1 + \beta_2 ICT > 0 \rightarrow$ urbanization improves ESI.

3.2.2 The non-monotonic relationship between urbanization-ICT nexus and environmental sustainability

To test whether ICT reduces the curvature that makes urbanization initially harmful to the environment, econometrically expressed as,

$$ESI_{it} = \alpha_i + \gamma_t + \beta_1 URBPOP_{it} + \beta_2 ICT_{it} + \beta_3 URBPOP_{it}^2 + \beta_4 ICT_{it}^2 + \beta_5 GDPpcit + \beta_6 GDPpcit^2 + \beta_7 CTVit + \varepsilon_{it} \quad (2)$$

$URBPOP_{it}^2$, ICT_{it}^2 and $GDPpcit^2$ capture a nonlinear (inverted-U or U-shape). Theoretically, we expect $\beta_4 > 0$ and $\beta_6 > 0$ to raise ESI and the relationship will be a U-shape if the coefficient $\beta_4 > 0$ and $\beta_6 > 0$ are positive. Initial ICT rollout is associated (negative) with environmental

costs leading to increased material footprints (production) and consumption (rising energy demand from data centers and telecommunications facilities often powered by fossil fuels, lowering ESI. While at low-income levels, GDP per capita is expected to display a negative linear relationship with environmental sustainability particularly in developing countries like West Africa because in the early stages of economic growth, the economies tend to rely heavily on natural resource extraction, energy-intensive production, and weakly regulated industrial expansion. But beyond a certain threshold ICT (β_4) and income level (β_6) begin to enhance environmental sustainability via investing in cleaner technologies, dematerialization and enforcing environmental regulations. If the results show the U-pattern ($\beta_1 < 0$ (Negative; initial decreasing ESI as urbanization increases), $\beta_4 > 0$ and $\beta_6 > 0$) are positive. (valid turning point or peak then rise ESI). In relation to EKC hypothesis, we confidently say "EKC holds for sustainability outcomes."

3.3 Construction of Composite Index of Environmental Sustainability

The results of the primary components are presented in Table 3.3. The environmental sustainability index, derived from the two primary components of environmental sustainability, accounts for approximately 50.97% of the overall variation in the distinct data, with an eigenvalue of 1.0195.

Table 3.3: Composite Index of Environmental Sustainability

Variable	Loading (PC1)	Eigen value	Contribution
Material footprint	-0.707107	1.019466	Lower MF better sustainability
Ecological footprint	0.707107	0.980534	Higher EF worse environmental sustainability

Note: PC - principal component.

Source: Author's computation (2025).

The high positive PC1 scores of ecological footprints contribute most strongly to PC1 driving environmental pressures. Conversely, negative scores of material footprints indicate ecologically lighter footprints and better sustainability. Overall, PC1 explains 50.97% which captures overall environmental pressure.

3.4 Estimation Techniques

The analytical foundation of this study is built on the Cross-Section Augmented Autoregressive Distributed Lag (CS-ARDL) estimator developed by Chudik and Pesaran (2015). The CS-ARDL framework, developed within the Common Correlated Effects (CCE) methodology, is specifically

designed for heterogeneous panel datasets that may exhibit cross-sectional dependence, dynamic relationships, and different orders of integration among variables. The method can control cross-sectional dependence, endogeneity, serial correlation, integrating features of the variables, and making short-term and long-term projections (Chudik & Pesaran; 2015). The model is expressed as follows:

$$\Delta ESI_{it} = \phi(ESI_{i,t-1} - \theta_i X_{it}) + \sum_{j=1}^p \gamma_{ij} \Delta ESI_{i,t-j} + \sum_{j=0}^q \delta_{ij} \Delta X_{i,t-j} + \mu_i + \epsilon_{it} \quad (3)$$

where ϕ is the error-correction speed (ECM term), θ_i captures long-run equilibria, X includes regressors, and lags are selected via information criteria. Results are robust to unit root tests (Im-Pesaran-Shin) confirming mixed I(0) and I(1) series.

4. Results and Discussions

The summary statistics for all variables used in the study are presented in Table 4.1, based on 312 observations. The descriptive analysis covers mean, standard deviation, skewness, and kurtosis across the cross-country panel data. The results show varying levels of dispersion among variables, some variables maintain low standard deviations such as (ESI = 0.992, URBPOP = 0.902, and INSQI = 0.449) relative to their average statistics (ESI = 4.329, URBPOP = 4.086, and INSQI = 1.249) implying stability and consistency. While high standard deviations, indicating substantial dispersion and strong heterogeneity across countries, are likely driven by uneven development conditions. The means and medians are closely aligned; for instance, the Environmental Sustainability Index (ESI) has a mean of 4.329 and a slightly higher median of 4.267, suggesting that a few lower values reduce the average. Skewness results indicate near-symmetry overall, with GDP per capita (GDPPC) exhibiting negative skewness (-1.25), reflecting a longer left tail due to more low-income observations, while other variables show mild positive skewness. All variables have kurtosis values greater than 3, confirming heavy-tailed distributions relative to normality. Following the descriptive statistics, a correlation matrix (Table 4.2) shows moderate relationships among the variables. Multicollinearity diagnostics further reveal no serious concerns, as all Variance Inflation Factor (VIF) values remain below 5.

Table 4.1 Descriptive Statistics

	ESI	URBPOP	ICT	GDPPC	IND	TRADEOPEN	ENEGCON	INSQI
Mean	4.329	4.086	5.661	1.684	6.913	61.49	46.12	1.249
Median	4.267	3.971	5.617	2.101	4.992	58.49	12.11	1.196
Std. Dev.	0.992	0.902	1.345	3.853	11.112	25.543	101.9	0.449
Skewness	3.732	0.740	2.273	-1.246	2.599	4.634	3.458	0.743
Kurtosis	42.14	3.963	15.46	22.46	18.89	23.79	14.38	5.225
Observations	312	312	312	312	312	312	312	312

Table 4.2 Correlation Matrix

Results of the Correlation Analysis									
	ESI	URBPO	ICT	GDPPC	IND	ENEGCONS	TRADEOPEN	INSQI	VIF
ESI	1								-
URBPOP	0.093	1							1.063
ICT	0.207	0.012	1						2.258
GDPPC	0.017	0.188	-0.082	1					1.191
IND	-0.157	-0.049	-0.024	0.295	1				1.158
ENEGCONS	-0.058	-0.123	0.015	0.017	0.082	1			1.018
TRADEOPEN	-0.014	-0.089	-0.066	0.057	0.018	-0.073	1		2.263

INSQI	-0.0103	0.031	0.109	-0.025	0.014	-0.183	-0.0233	1	1.043
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Source: Authors' computation (2025)

To ensure the panel regression results are reliable, the study first checks for cross-sectional dependence using Pesaran's CD test. The findings (Table 4.3) show that cross-sectional dependence is present, meaning that shocks affecting one country tend to spill over and influence others. Because of this interconnectedness, the feasible generalized least squares (FGLS) method is applied. FGLS is appropriate for the dataset especially since the time dimension is larger than the number of countries ($T > N$) and it helps correct issues related to cross-sectional correlation, heteroscedasticity, and serial correlation.

Table 4.3. Results of Cross-Sectional Dependence Test

Test	Statistic	P-Value	FGLS (CSD)	P-Value
Breusch-Pagan LM	142.7	0.000	63.95375	0.5485
Pesaran scaled LM	6.672	0.000	-0.178103	0.8586
Pesaran CD	3.089	0.002	1.364811	0.1723

P < (0.05); null hypothesis of no cross-sectional dependence is rejected

Source: Authors' computation (2025).

Given the nature of panel data, it is important to examine whether the slope coefficients are homogeneous across the cross-sectional units included in the analysis. In this regard, this study employs the Pesaran and Yamagata (2008) slope homogeneity test to assess whether the estimated coefficients are identical or vary across the individual units in the panel dataset.

Table 4.3 Homogeneity Test

	Delta	P-Value
	5.484	0.000
Adj.	7.666	0.000

Note: Null Hypothesis (H0): Slope coefficients are homogeneous (homogeneous panel). Alternative Hypothesis (H1): Slope coefficients are heterogeneous. If the P-value of the Δ (delta) or Δ_{adj} . statistic is less than 0.05, reject H0

Source: Authors' computation (2025).

Table 4.3 strongly rejects the assumption of parameter homogeneity across cross-sectional units, indicating significant slope and intercept heterogeneity. In macro-panel data, such heterogeneity is typically associated with cross-sectional dependence arising from unobserved common shocks and spillover effects. As a result, the use of first-generation panel estimators becomes inappropriate, motivating the adoption of second-generation panel methods. The analysis then moves to second-generation unit root tests.

Pesaran’s (2007) CIPS test, presented in Table 4.4, shows that the variables are stationary at their levels and first difference. With stationarity established, the study proceeds to examine whether the variables share a long-run equilibrium relationship. The Westerlund cointegration test (Table 4.5) confirms that such a long-run relationship exists, indicating that the variables move together over time and are cointegrated.

Table 4.4 Second-generation panel unit root test

Variable	CIPS				
	Constant		Constant and trend		
	Level	First Diff	Level	First Diff	I(D)
ESI	0.00000	-3.81064***	-2.31920	-3.53266***	I(1)
URBPOP	-1.43016	-2.39413**	-2.26629	-2.54605	I(1)
ICT	-1.55315	-3.63170***	-2.79710*	-	I(1/0)
GDPPC	-3.10943***	-	-3.00963**	-	I(0)
IND	-3.49217***	-	-4.64191***	-	I(0)
ENEGCONS	-3.01597***	-	-2.66008	-3.53171***	I(0/1)
TRADEOPEN	-1.82826	-4.52935***	-2.53718	-4.15936***	I(1)
INSQI	-2.03802	-3.00204***	-2.39935	-3.58944***	I(1)

Note: The superscript ***, **, and * denoted the significance with the 1%, 5% and 10% levels, respectively

Source: Authors’ computation (2025)

Table 4.5 Westerlund Cointegration Test

Variance ratio	Statistic	p-value
	3.0766	0.0010

Source: Authors’ computation (2025)

Table 4.6: Results of Estimation (Direct Impact)

Variable	CS-ARDL	AMG
	Dependent Variable: Environmental Sustainability (ESI)	
	Long run estimations	
LnURBPOP	-16.38* (0.087)	-7.517** (0.023)
ICT	-6.296 (0.331)	-1.045 (0.305)
URBPOP_ ICT	0.014** (0.028)	0.164 (0.400)
LnGDPPC	0.062 (0.974)	0.243* (0.087)
IND	0.187 (0.664)	0.024 (0.420)
TRADEOPEN	-0.007* (0.066)	-0.003 (0.407)
LnENEGCON	-0.359 (0.758)	0.202 (0.691)
INSQI	-0.294** (0.021)	-0.069 (0.536)
CD statistic	-0.130 (0.899)	
Wald ch2		21.48 (0.006)
RMSE	0.24	0.2181
Short run estimations		
L.ESI		-0.133 (0.362)
LnURBPOP		10.14*

	(0.061)
ICT	-1.030 (0.416)
URBPOP_ ICT	0.231 (0.347)
LnGDPPC	-1.825** (0.042)
IND	0.023 (0.540)
TRADEOPEN	-0.002** (0.027)
LnENEGCON	0.104 (0.887)
INSQI	-0.281 (0.140)
ECT	-1.133 (0.000)

Note: Probability of each statistic is placed in parentheses (). The superscript ***, **, and * denoted the significance with the 1%, 5% and 10% levels, respectively

Source: Researcher' computation (2025).

The empirical results in Table 4.6 shed light on how urbanization and ICT development jointly influence environmental sustainability. Both CS-ARDL and AMG were employed to reduce the likelihood of model misspecification. Cross-Sectionally Augmented ARDL (CS-ARDL) technique was initially specified to capture dynamic, short-run, and long-run relationships among heterogeneous panels with cross-sectional dependence while Augmented Mean Group (AMG) is used to specifically estimate the long-run effect and ensure the robustness of the regression results, as shown in Table 4.6.

In the long run, urban population growth has a negative and significant effect. This reports that a 1% increase in URBPOP would decrease environmental sustainability by 16.38% when other

variables are held constant. This implies that rapid urbanization is likely to lead to environmental degradation, meaning that as cities expand, environmental quality tends to decline. This study provides evidence to support the study of Radoine, Bajja, Chenal & Ahmed (2022) who revealed that urbanization increases environmental degradation. Similarly, ICT penetration shows a negative and insignificant effect (-6.296), indicating that change in ICT does not significantly affect environmental sustainability. The interaction between urbanization and ICT (URBPOP_ICT) is also positive and highly significant. This result shows that a 1% increase in URBPOP_ICT would increase environmental quality by 0.014% in the long run, when other variables are held constant,

This means ICT serves as a moderating force: although urbanization on its own harms the environment, the negative effect of urbanization is reduced when ICT increases alongside urban growth. This finding supports the findings of Chatti & Majeed (2022) who found that the interaction between ICTs and urbanization reduces pollution for developed countries.

In contrast, trade openness (TRADEOPEN) and institutional quality (INSQI) exert a negative effect on environmental sustainability. This suggests that higher trade (imports and exports) is related to environmental degradation. It means that trade expansion leads to increased industrial output, energy use, and CO₂ emissions. The negative effect of institutional quality (INSQI) implies that institutional indicators are not translating into better environmental outcomes, meaning that environmental regulations may exist on paper but lack effective implementation.

For consistency of the estimates, the AMG estimator was employed to estimate the long-run results. In Table 4.6, the AMG results reveal that urbanization (URBPOP) has a significant and negative effect on environmental sustainability among selected West African countries. Similarly, ICT has negative and insignificant effects on environmental sustainability among selected West African countries. This aligns with the long-run CS-ARDL estimation results. The findings also show that GDP per capita (GDPPC) had positive and significant effects on environmental sustainability. This indicates that a 1% increase in GDP per capita (GDPPC) would enhance environmental sustainability by 0.243% when other variables are held constant. This implies that GDP per capita income enhances environmental outcomes in the sub-region. This positive effect of GDPPC on environmental sustainability implies that long-run higher income is associated with improvements

in environmental quality. This result possibly supports the findings of Bosah et al. (2021), Ntarmah et al. (2021), and Sheraz et al. (2021), who reveal that GDP improves environmental quality.

In the short run, the patterns differ. Urbanization (URBPOP) exerts positive and significant effect (10.14) on environmental sustainability. This suggests that immediate effect of urbanization initially contributes to improved environment, possibly due to improved ICT infrastructure. The short-run interaction term is insignificant, confirming that ICT does not moderate environmental impacts instantly; its benefits accumulate over time as infrastructure and institutions adapt. Control variables also show mixed short-run signs, reflecting temporary fluctuations rather than structural effects.

The error correction term (-1.133) is negative and significant, indicating rapid adjustment, with about 133% of deviations corrected annually, suggesting fast convergence back to the long-run equilibrium path. The study diagnostic test reveals a CD statistic of -0.130 with p-value of 0.899 which implies the null hypothesis of no cross-sectional dependence cannot be rejected. This means that no evidence of cross-sectional dependence in the residuals ($p > 0.05$). The CS-ARDL augmentation has successfully addressed any potential cross-sectional dependence in the data. The use of CS-ARDL approach is valid. The Wald chi2 value is significant at the 1% level, suggesting that the distribution of the variables fits well with the ESI model. The Root Mean Square Errors (RMSE) of 0.24 and 0.2181 indicates a reasonable model fit.

Table 4.7: Results of Estimation (Non-Monotonic)

Variable	CS-ARDL	AMG
	Dependent Variable: Environmental Sustainability (ESI)	
	Long run estimations	
LnURBPOP	469.8** (0.033)	32.03* (0.087)
ICT	-0.002* (0.068)	0.496 (0.142)

LnGDPPC	-1.142* (0.056)	-94.33** (0.040)
LnSQURBPOP	0.041*** (0.000)	-1.015 (0.688)
SQICT	0.002* (0.054)	0.299** (0.045)
LnSQGDPPC	0.072* (0.058)	5.928** (0.039)
IND	0.004 (0.227)	-0.008 (0.185)
TRADEOPEN	-0.075* (0.074)	-0.001 (0.523)
LnENEGCON	-0.004 (0.771)	0.396* (0.077)
INSQI	0.011 (0.904)	-0.116 (0.101)
CD statistic	-0.65 (0.517)	
Wald ch2		14.1 (0.067)
RMSE	1.80	0.1814
Short run estimations		
L.ESI		0.305* (0.058)
LnURBPOP		470.75** (0.032)
ICTDI		0.948 (0.136)
LnGDPPC		-176.69**

	(0.021)
LnSQURBPOP	-12.03 (0.576)
SQICT	0.391 (0.342)
LnSQGDPPC	10.57 (0.132)
IND	-0.030 (0.247)
TRADEOPEN	-0.005* (0.073)
LnENEGCON	0.054 (0.904)
INSQI	-0.282** (0.048)
ECT	-0.694*** (0.000)

Note: Probability of each statistic is placed in parentheses (). The superscript ***, **, and * denoted the significance with the 1%, 5% and 10% levels, respectively

Source: Researcher' computation (2025).

The analysis also explores whether environmental outcomes respond to urbanization and ICT in a non-linear way. Results of CS-ARDL and AMG long run estimations in Table 4.7 show that URBPOP exerts a positive and significant coefficient of 469.8. Similarly, URBPOP has a positive and significant effect on environmental sustainability among the selected West African countries. This implies that increased urban population (as a measurement of urbanization) is associated with better environmental outcomes. Further increased urbanization (lnSQURBPOP is positive and significant) leads to higher environmental improvements i.e., a 1% increase in urbanization (URBPOP) would enhance environmental sustainability by 0.041%. This result aligns with the empirical findings of Khan et al. (2023) which indicated urbanization reduced CO2 emissions in the long run. The results of both URBPOP and SQURBPOP indicate that the relationship with environmental sustainability is monotonic within this study.

The results also reveal that initial ICT has a negative and statistically significant effect on environmental sustainability, this suggests that in the long run, a 1% increase in ICT in the selected West African countries would decrease environmental sustainability by 0.002% when other variables are held constant. This implies that the negative effect leads to increased material footprints (production) and ecological footprints (consumption) of ICT thereby lowering environmental sustainability (ESI). The result is consistent with the study of Avom, et al (2020) who found the negative effect of ICT on environmental quality due to the inefficient use of energy by a large number of ICT equipment. The non-linear specifications of SQICT exhibit positive and significant coefficients of 0.002 and 0.299, suggesting that increased ICT adoption enhances environmental sustainability. This implies that an increase in ICT leads to improved environmental outcomes.

Moreso, GDP per capita income (lnGDPPC) shows a negative and significant effect on environmental sustainability, i.e., a 1% increase in GDP per capita income would lower environmental sustainability by 1.142% and 94.33%. While nonlinear (lnSQGDPPC) relationship exerts positive (0.072 and 5.928) and significant coefficients i.e., a 1% increase in higher GDP per capita income would lead to environmental improvement by 0.072% and 5.928%. This implies that at low-income levels, GDP per capita initial decreasing ESI but beyond a certain threshold, at higher income level begins to enhance environmental sustainability. These empirical findings agree with the results of Narayan and Narayan 2010; Adu and Denkyirah 2017; Halliru et al. 2020; Ntarmah et al. 2021; Ahmad et al. 2022).

According to the findings, the effect of both linear and non-linear ICT and GDPPC on the environmental sustainability is described by the U- shaped pattern. The observed U-shaped pattern provides confirmation of the EKC hypothesis when environmental sustainability is measured using a positive composite index. Similar to the Environmental Kuznets Curve, a relationship suggests that environmental degradation initially increases with income level until a certain threshold. After this threshold, an increase in income level lessens environmental degradation. This indicates that higher levels of income are associated with reductions in environmental degradation in the long run.

Furthermore, trade openness exhibits a significant and negative effect on environmental sustainability. In fact, the coefficient of trade openness is -0.07 in the linear specification implies that a 1% increase in trade openness decreases environmental sustainability by 0.07% if all other factors remain constant. This suggests that an increase in trade openness is associated with decline in environmental sustainability. This finding contradicts the results of Saboori et al. (2016) and Avom, et al (2020) who show that an increase in the trade openness is associated to an improvement in environmental quality.

Energy consumption has a positive (0.396) and statistically significant effect on environmental sustainability in the long run, illustrating that a 1% increase in ENEGCON enhances environmental outcomes by 0.396% when other variables are held constant. This indicates that higher energy consumption is associated with improvements in energy efficiency or a gradual transition toward cleaner and efficient energy systems. This empirical result agrees with the finding of Kirikkaleli and Adebayo (2020); Radoine, Bajja, Chenal and Ahmed (2022) who indicated that effective energy utilization plays a vital role in mitigating the CO₂ emissions level.

Reports from the short-run estimates indicate that the coefficient of first lagged of environmental sustainability index (ESI) is positive and statistically significant at 10% level indicating that the previous year of environmental sustainability index (ESI) has a positive impact on the current year of environmental sustainability index (ESI).

URBPOP exerts a positive and significant coefficient of 470.75 implying that increased urban population (URBPOP) is associated with better environmental outcomes. GDP per capita income exhibits a negative and significant effect; it suggests that a 1% increase in early income level (GDPPC) would decline environmental sustainability by 176.69%. This implies that negative effect of GDP per capita in the short run is likely to lead to greater environmental degradation due to increased resource and energy consumption, and weak regulatory frameworks.

The term of error correction ($ECT = -0.694$, $P < 0.00$) is negative and significant, as hypothesized, suggesting that the any short-term deviation from the long-run equilibrium is corrected at a rate of approximately 69.4% per period, confirming strong adjustment towards long-run stability. The

AMG approach produced almost same results as the earlier method, demonstrating the reliability and consistency of the results of the CS-ARDL technique.

The results of the CS-ARDL method show that ICT and GDPPC have a significant effect on environmental sustainability in the long term, while SQICT and SQGDPPC significantly enhance environmental sustainability, describing the U- shaped pattern. This validates the inverted U-shaped EKC hypothesis in the long run for the selected West African countries. However, in the short term, the EKC hypothesis has not yet been confirmed. The long run estimates also support predictions from Ecological Modernization Theory (EMT), which argues that technological upgrades and strong governance improve environmental outcomes. Overall, the results are fully consistent with both EKC and EMT expectations.

In terms of diagnostic statistics, the Wald chi2 values are significant at the 10% level, suggesting that the distribution of the variables fits well with the ESI model. The CD statistic of -0.65 with p-value of 0.5169 which implies the null hypothesis of no cross-sectional dependence cannot be rejected. This means that no evidence of cross-sectional dependence in the residuals ($p > 0.05$). The CS-ARDL augmentation has successfully addressed any potential cross-sectional dependence in the data. The use of CS-ARDL approach is valid. The Root Mean Square Errors (RMSE) of 1.80 indicates a reasonable model fit.

5. Conclusion and Policy Implications

The relationship between urbanization, ICT growth, and environmental sustainability in West Africa is both dynamic and complex. While urbanization has supported economic development by attracting investment and driving industrialization, it also creates significant environmental pressures. Understanding how these forces interact is crucial for shaping sustainable development strategies in emerging economies. Our empirical results from CS-ARDL framework across 12 West African countries reveal a monotonic relationship between urbanization and environmental sustainability in the selected West African countries. However, ICT and GDPPC have a significant effect on environmental sustainability in the long run. The positive effect of SQICT and SQGDPPC significantly enhance environmental sustainability. Thus, their impact validates the EKC hypothesis in the long run for the selected West African countries. This indicates a stronger

connection between increased ICT adoption, higher income level and better environmental outcomes in West Africa. Therefore, suggests that West African countries could collectively gain from EKC and EMT arguments.

In this regard, the findings from this study offer fresh evidence on how sustainability evolves in regions experiencing rapid city expansion and growing digital adoption. The study concludes that achieving environmental sustainability in West Africa requires carefully balancing urban growth with technological progress, strong governance, and cleaner energy transitions. Policymakers should focus on guiding urban expansion, promoting ICT within sustainable energy frameworks, improving institutional quality, and accelerating circular and low-material economic models. Such efforts will allow the sub-region to benefit from urbanization and digitalization while protecting environmental integrity.

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